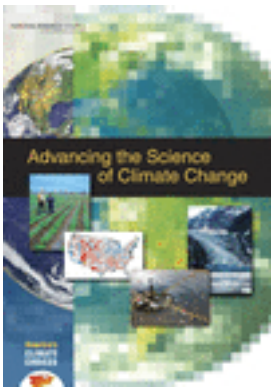
Free Summary

Advancing the Science of Climate Change



America's Climate Choices: Panel on Advancing the Science of Climate Change; National Research Council
ISBN: 978-0-309-14588-6, 506 pages, 7 x 10, paperback (2010)

Summary

Science has made enormous inroads in understanding climate change and its causes, and is beginning to develop a strong understanding of current and potential impacts that will affect people today and in coming decades. This understanding is crucial because it allows decision makers to place climate change in the context of other large challenges facing the nation and the world. There are still some uncertainties, and there always will be in understanding a complex system like Earth's climate. Nevertheless, there is a strong, credible body of evidence, based on multiple lines of research, documenting that climate is changing, and that these changes are in large part caused by human activities. While much remains to be learned, the core phenomenon, scientific questions, and hypotheses have been examined thoroughly and have stood firm in the face of serious scientific debate and careful evaluation of alternative explanations.

As a result of the growing recognition that climate change is underway and poses serious risks for both human societies and natural systems, the question that decision makers are asking has expanded from "what is happening" to "what is happening and what can we do about it?" Scientific research can help answer both of these important questions. In addition to the extensive body of research on the causes and consequences of climate change, there is a growing body of knowledge about technologies and policies that can be used to limit the magnitude of future climate change, a smaller but expanding understanding of the steps that can be taken to adapt to climate change, and a growing recognition that climate change will need to be considered in actions and decisions across a wide range of sectors and interests. Advice on prudent short-term actions and long-term strategies in these three areas can be found in the companion reports *Limiting the Magnitude of Future Climate Change* (NRC, 2010b), *Adapting to the Impacts of Climate Change* (NRC, 2010c), and *Informing an Effective Response to Climate Change* (NRC, 2010a).

This report, *Advancing the Science of Climate Change*[2], reviews the current scientific evidence regarding climate change and examines the status of the nation's scientific research efforts. It also describes the critical role that climate change science, broadly defined, can play in developing knowledge and tools to assist decision makers as they act to respond to climate change. The report explores seven cross-cutting research themes that should be included in the nation's climate change research enterprise, and recommends a number of actions to advance the science of climate change—a science that includes and increasingly integrates across the physical, biological, social, health, and engineering sciences. Overall, the report concludes that:

(1) Climate change is occurring, is caused largely by human activities, and poses significant risks for a broad range of human and natural systems; and

(2) The nation needs a comprehensive and integrated climate change science enterprise, one that not only contributes to our fundamental understanding of climate change but also informs and expands America's climate choices.

---

[2] The statement of task of the Panel on Advancing the Science of Climate Change can be found in Appendix B (and is summarized in Box S-1), and the panel membership is included in Appendix C.

WHAT WE KNOW ABOUT CLIMATE CHANGE

Conclusion 1: Climate change is occurring, is caused largely by human activities, and poses significant risks for—and in many cases is already affecting—a broad range of human and natural systems.

This conclusion is based on a substantial array of scientific evidence, including recent work, and is consistent with the conclusions of recent assessments by the U.S. Global Change Research Program (USGCRP, 2009a, and others), the Intergovernmental Panel on Climate Change's Fourth Assessment Report (IPCC, 2007a-d), and other assessments of the state of scientific knowledge on climate change. Both our assessment—the details of which can be found in Chapter 2 and Part II (Chapters 6-17) of the report—and these previous assessments place high or very high confidence[3] in the following findings:

- Earth is warming. Detailed observations of surface temperature assembled and analyzed by several different research groups show that the planet's average surface temperature was 1.4 ºF (0.8 ºC) warmer during the first decade of the 21st century than during the first decade of the 20th century, with the most pronounced warming over the past three decades. These data are corroborated by a variety of independent observations that indicate warming in other parts of the Earth system, including the cryosphere (snow and ice covered regions), the lower atmosphere, and the oceans.
- Most of the warming over the last several decades can be attributed to human activities that release carbon dioxide (CO_2) and other heat-trapping greenhouse gases (GHGs) into the atmosphere. The burning of fossil fuels—coal, oil, and natural gas—for energy is the single largest human driver of climate change, but agriculture, forest clearing, and certain industrial activities also make significant contributions.
- Natural climate variability leads to year-to-year and decade-to-decade fluctuations in temperature and other climate variables, as well as significant regional differences, but cannot explain or offset the long-term warming trend.
- Global warming is closely associated with a broad spectrum of other climate changes, such as increases in the frequency of intense rainfall, decreases in snow cover and sea ice, more frequent and intense heat waves, rising sea levels, and widespread ocean acidification.
- Individually and collectively, these changes pose risks for a wide range of human and environmental systems, including freshwater resources, the coastal environment, ecosystems, agriculture, fisheries, human health, and national security, among others.
- Human-induced climate change and its impacts will continue for many decades, and in some cases for many centuries. The ultimate magnitude of climate change and the severity of its impacts depend strongly on the actions that human societies take to respond to these risks.

---

[3] As discussed in Appendix D, high confidence indicates an estimated 8 out of 10 or better chance of a statement being correct, while very high confidence indicates a 9 out of 10 or better chance.

Despite an international agreement to stabilize GHG concentrations "at levels that would avoid dangerous anthropogenic interference with the climate system" (UNFCCC 1992, 2009), global emissions of CO_2 and several other GHGs continue to increase. Projections of future climate change, which are based on computer models of how the climate system would respond to different scenarios of future human activities, anticipate an additional warming of 2.0 to 11.5 ºF (1.1 to 6.4 ºC) over the 21st century. A separate NRC report, expected in summer 2010, provides an analysis of impacts at different magnitudes of future climate change.

In general, it is reasonable to expect that the magnitude of future climate change and the severity of its impacts will be larger if actions are not taken to limit its magnitude and adapt to its impacts. However, as with all projections of the future, there will always be some uncertainty regarding the details of future climate change. Several factors contribute to this uncertainty:

- Projections of future climate change depend strongly on how human societies decide to produce and use energy and other resources in the decades ahead.
- Human-caused changes in climate overlap with natural climate variability, especially at regional scales.
- Certain Earth system processes—including the carbon cycle, ice sheet dynamics, and cloud and aerosol processes—are not yet completely understood or fully represented in climate models, but could potentially have a strong influence on future climate changes.
- Climate change impacts typically play out at local-to-regional scales, but processes at these scales are not as well represented by models as continental-to-global scale changes.
- The impacts of climate change depend on how climate change interacts with other global and regional environmental changes, including changes in land use, management of natural resources, and emissions of other pollutants.
- The impacts of climate change also depend critically on the vulnerability and adaptive capacity of human and natural systems, which can vary widely in space and time and generally are not as well understood as changes in the physical climate system.

Climate change also poses challenges that set it apart from other risks with which people normally deal. For example, many climate change processes have considerable inertia and long time lags, so it is mainly future generations that will have to deal with the consequences (both positive and negative) of decisions made today. Also, rather than smooth and gradual climate shifts, there is the potential that the Earth system could cross tipping points or thresholds that result in abrupt changes. Some of the greatest risks posed by climate change are associated with these abrupt changes and other climate "surprises" (unexpected changes or impacts), yet the likelihood of such events is not well known. Moreover, there has been comparatively little research on the impacts that might be associated with "extreme" climate change—for example, the impacts that could be expected if global temperatures rise by 10 °F (6 °C) or more over the next century. Thus, while it is clear that the Earth's future climate will be unlike the climate that ecosystems and human societies have become accustomed to during the last 10,000 years, the exact magnitude of future climate change and the nature of its impacts will always remain somewhat uncertain.

Decision makers of all types, including businesses, governments, and individual citizens, are beginning to take actions to reduce the risks posed by climate change—including actions to limit its magnitude and actions to adapt to its impacts. Effective management of climate risks

will require decision makers to take actions that are flexible and robust, to learn from new knowledge and experience, and to adjust future actions accordingly. The long time lags associated with climate change and the presence of differential vulnerabilities and capacities to respond to climate change likewise represent formidable management challenges. These challenges also have significant implications for the nation's climate science enterprise.

A NEW ERA OF CLIMATE CHANGE RESEARCH

Conclusion 2: The nation needs a comprehensive and integrative climate change science enterprise, one that not only contributes to our fundamental understanding of climate change but also informs and expands America's climate choices.

Research efforts over the past several decades have provided a wealth of information to decision makers about the known and potential risks posed by climate change. Experts from a diverse range of disciplines have also identified and developed a variety of actions that could be taken to limit the magnitude of future climate change or adapt to its impacts. However, much remains to be learned. Continued investments in scientific research can be expected to improve our understanding of the causes and consequences of climate change. In addition, the nation's research enterprise could potentially play a much larger role in addressing questions of interest to decision makers as they develop, evaluate, and execute plans to respond to climate change. Because decisions always involve value judgments, science cannot prescribe the decisions that should be made. However, scientific research can play a key role by informing decisions and by expanding and improving the portfolio of available options.

Cross-Cutting Themes for Climate Change Research

This report identifies seven cross-cutting research themes, grouped into three general categories, that collectively span the most critical research needs for understanding climate change and for informing and supporting effective responses to it.

Research to Improve Understanding of Human-Environment Systems:

1) *Climate Forcings, Responses, Feedbacks and Thresholds in the Earth System*
   Some examples of research needs that fall under this theme include improved understanding of climate sensitivity, ice sheet dynamics, climate-carbon interactions, crop and ecosystems responses to climate changes (in interaction with other stresses), and changes in extreme events.
2) *Climate-Related Human Behaviors and Institutions*
   Some examples include improving understanding of human behavior and decision making in the climate context, institutional impediments to limiting or adaptation responses, determinants of consumption, and drivers of climate change.

Research to Support Effective Responses to Climate Change:

3) *Vulnerability and Adaptation Analyses of Coupled Human-Environment Systems*
   Some examples include developing methods and indicators for assessing vulnerability[4] and developing and assessing integrative management approaches to respond effectively to the impacts of climate change on coasts, freshwater resources, food production systems, human health, and other sectors.
4) *Research to Support Strategies for Limiting Climate Change*
   Some examples include developing new and improved technologies for reducing GHG emissions (such as enhanced energy efficiency technologies and wind, solar, geothermal-based and other energy sources that emit few or no GHGs), assessing alternative methods to limit the magnitude of future climate change (such as modifying land use practices to increase carbon storage or geoengineering[5] approaches), and developing improved analytical frameworks and participatory approaches to evaluate trade-offs and synergies among actions taken to limit climate change.
5) *Effective Information and Decision-Support Systems*
   Some examples include research on risk communication and risk management processes; improved understanding of individual, societal, and institutional factors that facilitate or impede decision making; analysis of information needs and existing decision support activities, and research to improve decision-support products, processes, and systems.

Tools and Approaches to Improve Both Understanding and Responses:

6) *Integrated Climate Observing Systems*
   Some examples include efforts to ensure continuity of existing observations; develop new observational capacity for critical physical, ecological, and social variables; ensure that current and planned observations are sufficient both to continue building scientific understanding of and support more effective responses to climate change (including monitoring to assess the effectiveness of responses); and ensure adequate emphasis and support for data assimilation, analysis, and management.
7) *Improved Projections, Analyses, and Assessments*
   Some examples include advanced models for analysis and projections of climate forcing, responses, and impacts, especially at regional scales; and integrated assessment models and approaches—both quantitative and non-quantitative—for evaluating the advantages and disadvantages of, and the trade-offs and co-benefits[6] among, various options for responding to climate change.

---

[4] Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (NRC, 2010c)

[5] The term *geoengineering* refers to deliberate, large-scale manipulations of Earth's environment designed to offset some of the harmful consequences of GHG-induced climate change. Geoengineering encompasses two very different classes of approaches: CO_2 removal and solar radiation management. See Chapter 15 for details.

[6] A co-benefit refers to an additional benefit resulting from an action undertaken to achieve a particular purpose, but that is not directly related to that purpose.

These seven themes and the range of research questions within them are explored in Chapter 4 (and additional discussion of specific research needs can be found in Chapters 6-17). Because progress in any one of these themes is related to progress in others, all seven will need to be pursued, simultaneously or at least iteratively. The nation currently has the capabilities and capacity to make incremental progress in some of these key research areas, but making more dramatic improvements in our understanding of and ability to respond to climate change will require several fundamental alterations in the support for and organization and conduct of climate change research.

RECOMMENDATIONS

Recommendation 1: The nation's climate change research enterprise should include and integrate disciplinary and interdisciplinary research across the physical, social, biological, health, and engineering sciences; focus on fundamental, use-inspired research that contributes to both improved understanding and more effective decision making; and be flexible in identifying and pursuing emerging research challenges.

Climate change research needs to be integrative and interdisciplinary. Climate change involves many aspects of the Earth system, as well a wide range of human activities, and both climate change and actions taken to respond to climate change interact in complex ways with other global and regional environmental changes. Understanding climate change, its impacts, and potential responses thus inherently requires integration of knowledge bases from many different scientific disciplines, including the physical, social, biological, health, and engineering sciences, and across different spatial scales of analysis, from local to global. Developing the science to support choices about climate change also requires engagement of decision makers and other stakeholders, as discussed below.

Climate change research should focus on fundamental, use-inspired research. This report recognizes the need for scientific research to both improve understanding of climate changes and assist in decision making related to climate change. In categorizing these types of scientific research, we found that terms such as "pure," "basic," "applied," and "curiosity driven" have different definitions across communities, are as likely to cause confusion as to advance consensus, and are of limited value in discussing climate change. More compelling, however, is the categorization offered by Stokes (1997) who argues that two questions should be asked of a research topic: Does it contribute to fundamental understanding? Can it be expected to be useful? Research that can answer yes to both of these questions, or "fundamental, use-inspired research," warrants special priority in the realm of climate change research.

Climate change research should support decision making at local, regional, national, and international levels. Many choices about how to respond to climate change fundamentally involve values and ethics, and thus cannot be based on science alone. However, scientific research can inform and guide climate-related decisions in a variety of ways. Continued research on the causes, mechanisms, and consequences of climate change will help clarify the risks that climate changes pose to human and natural systems. Science can help identify new options and strategies for limiting the magnitude of climate change or adapting to its impacts, as well as help improve existing options. Science also plays the key role of evaluating the advantages and disadvantages associated with different responses to climate change, including unintended

consequences, tradeoffs, and co-benefits among different sets of actions. Finally, scientific research on new, more effective information-sharing and decision-making processes and tools can assist decision making.

Climate change research needs to be a flexible enterprise, able to respond to changing knowledge needs and support adaptive risk management and iterative decision making. Many resource and infrastructure decisions, from storm sewer planning to crop planting dates, will be made in the context of continuously evolving climate conditions as well as ongoing changes in other environmental and human systems. Decision makers would thus be well advised to employ iterative and adaptive risk management[7] strategies as they make climate-related decisions. The nation's scientific enterprise will be increasingly called upon to provide the up-to-date, decision-specific information that such strategies require. Furthermore, as actions to limit and adapt to climate change—many of them never tried before—are taken, decision makers will need to understand and take the consequences of these actions into account. This will place increased demands on scientific monitoring, modeling, and analysis activities. To meet these evolving needs, the nation's climate research enterprise will itself need to be flexible and adaptive, and to practice "learning by doing" as it provides decision makers with the information they need to make effective decisions.

Recommendation 2: Research priorities for the federal climate change research program should be set within each of the seven cross-cutting research themes outlined above. Priorities should be set using the following three criteria:

(1) Contribution to improved understanding
(2) Contribution to improved decision making
(3) Feasibility of implementation, including scientific readiness and cost

Progress in the seven cross-cutting research themes would advance the science of climate change in ways that are responsive to the nation's needs for information. Progress in all seven themes is needed, but priorities will ultimately need to be set within them. The development of more comprehensive, exhaustive, and prioritized lists of specific research needs within each theme should involve members of the relevant research communities, taking into account that it is far more challenging to identify and evaluate key uncertainties and information needs in understudied areas than in established research fields. It is critical that priority setting also include the perspective of societal need, which necessitates input from decision makers and other stakeholders. Finally, feasibility of implementation, including scientific readiness, cost, and other practical, institutional, and managerial concerns, will be needed to ensure effectiveness. Chapter 5 provides additional details on priority setting.

[7] Adaptive (or iterative) risk management refers to an ongoing decision-making process that takes known and potential risks and uncertainties into account and periodically updates and improves plans and strategies as new information becomes available.

Recommendation 3: The federal climate change research program, working in partnership with other relevant domestic and international bodies, should redouble efforts to develop, deploy, and maintain a comprehensive observing system that can support all aspects of understanding and responding to climate change.

Long-term, stable, and well-calibrated observations across a spectrum of human and environmental systems are essential for diagnosing and understanding climate change and its impacts. The suite of needed observations includes measurements of physical, biological, ecological, and socio-economic processes, and includes both remotely sensed and *in situ* data across a range of scales. Observations are also critical for developing, initializing, and testing models of future human and environmental changes, and for monitoring and improving the effectiveness of actions taken to respond to climate change. However, many observing systems are in decline, putting our ability to monitor and understand future changes at risk. Stemming this decline should be a top priority. Responding effectively to climate change will also require new observational capabilities to monitor and evaluate progress in limiting climate change and adapting to its impacts, as well as to monitor known risks and identify new or emerging risks as climate change unfolds. All of these data need to be archived, checked for quality, and made readily accessible to a wide range of users, keeping in mind that many climate-related decisions require information of many different types and scales.

Hence, there is a critical need to develop, deploy, and maintain a robust infrastructure for collecting and archiving a wide range of climate and climate-related data, integrating data collected on different systems, and ensuring that the data are reliable, accurate, and easily accessible. The federal climate research program is the obvious entity for leading the development of such a coordinated, comprehensive, and integrated climate observing system, and ensuring that the system facilitates both improved understanding and more effective decision making. However, other relevant partners, including the domestic and international research communities and action-oriented programs at all spatial scales, also need to be engaged in system design, deployment, and maintenance. Critical steps include reviewing current and planned observational assets, identifying critical climate monitoring and measurement needs, and developing a comprehensive strategy to meet these needs, including data management and stewardship activities. The climate observing system should be coordinated with other environmental and social data collection efforts to take advantage of synergies and ensure interoperability. Finally, careful balancing is needed to ensure that resources are used effectively, that investments in one kind of observation do not impede the ability to invest in others, and that the full spectrum of most critical observations are collected and made available for diverse uses.

Recommendation 4: The federal climate change research program should work with the international research community and other relevant partners to support and develop advanced models and other analytical tools to improve understanding and assist in decision making related to climate change.

Enhanced modeling capabilities, including improved representations of underlying human and Earth system processes, are needed to support efforts to understand, limit, and adapt to climate change. Improvements are especially needed in integrated Earth system models to

allow more thorough examination of climate-related feedbacks and the possibility of abrupt changes, regional-scale projections of climate change and its impacts, and integrated assessment activities that explicitly link coupled human-environment systems. Also critical are more informative and comprehensive scenarios of future human activities that influence or are influenced by climate, and models and analyses of the effects of different actions (and combinations of actions) taken to adapt to climate change or limit its magnitude. Information on decadal time scales is particularly relevant to many climate-related decisions. Improvements in all of these areas go hand in hand with improvements in fundamental understanding, for example of processes and mechanism of regional climate variability and change. Improvements in models and other analytical tools also support decision making by allowing more thorough and comprehensive analyses of the economic, social, and environmental consequences of climate change and of actions taken to respond.

Adequate computational resources are critical for Earth system models, regional climate models, integrated assessment models, impacts-adaptation-vulnerability models, climate forcing scenario development efforts, and other tools for projecting future changes. Near-term progress would benefit from improvements in and access to high performance computing. As with observations, efforts are needed to ensure that the output from models, analyses, and assessments are appropriately managed, undergo continuing development, and actually inform decision-making processes at appropriate levels. The federal climate change research program should lead the development of a strategy for dramatically improving and integrating regional climate modeling, global Earth system models, and various integrated assessment, vulnerability, impact, and adaptation models. To ensure the success of this strategy, the program and its partners should take steps to increase the computational and human resources available to support a wide range of modeling efforts and ensure that these efforts are linked with both the national observing system strategy and with efforts to support effective decision making.

Recommendation 5: A single federal interagency program or other entity should be given the authority and resources to coordinate and implement an integrated research effort that supports improving both understanding of and responses to climate change. If several key modifications are made, the U.S. Global Change Research Program could serve this role.

There are several ways that climate change research at the federal level could be organized to achieve a broad, integrated, and decision-relevant research effort capable of coordinating and leading the nation's broader climate change research enterprise. After reviewing several options (see Chapter 5), the panel came to the conclusion that the Global Change Research Act of 1990, which established the U.S. Global Change Research Program (USGCRP), provides the legislative authority needed to implement a strategically integrated climate change research program (GCRA, 1990). The USGCRP is capable of implementing the other recommendations offered in this report, provided that several key modifications are made to its current structure, goals, and practices.

The USGCRP has been highly successful on many fronts, including in elucidating the causes and some of the impacts of climate change. However, institutional issues and other factors have resulted in critical knowledge gaps, including a number of the research needs identified in this report (see also NRC, 2009l). Other persistent criticisms of the program include inadequate support for and progress in social science research, decision support activities, and

integration across disciplines. To better support improvements in our understanding of climate change and effective responses to it, the USGCRP will need to establish improved mechanisms for identifying and addressing these and other weaknesses and gaps, as well as the barriers that give rise to such gaps. The USGCRP also needs to establish more effective mechanisms to interact with decision makers and other stakeholders.

To ensure progress in the seven key research themes identified above, and implement the other recommendations offered in this report, the USGCRP will need high-level leadership. This includes effective and forward-looking leadership of the program itself as well as supportive leaders in its partner agencies. To effectively shape and govern an interagency research effort, the program also needs expanded budgeting oversight and authority to coordinate and prioritize climate change research across agencies. The importance of effective leadership, with adequate support and programmatic and budgetary authority, has been recognized in several NRC reviews of the USGCRP (see Chapter 5 and Appendix E). Support and oversight from institutions with overarching authority, such as the Office of Management and Budget, the Office of Science and Technology Policy, and relevant Congressional committees, will be essential, as will a comprehensive, inclusive, and ongoing strategic planning process.

Recommendation 6: The federal climate change research program should be formally linked with action-oriented response programs focused on limiting the magnitude of future climate change, adapting to the impacts of climate change, and informing climate-related actions and decisions, and, where relevant, should develop partnerships with other research and decision-making entities working at local to international scales.

The engagement of institutions at all levels and of all sorts—academic, governmental, private sector, and not-for-profit—will be needed to meet the challenges of climate change. By working collaboratively with action-oriented programs, both at the federal level and across the country, the federal climate change research program can help ensure that the nation's responses to climate change are as effective as possible. For example, scientific knowledge about the impacts of climate change and about the vulnerability and adaptive capacity of different human and environmental systems—which typically requires analysis focused at local-to-regional scales—is critical for developing and assessing adaptation measures. Likewise, research on human behavior, institutions, and decision-making processes, products, and tools can contribute to programs designed to inform decision makers and other stakeholders about climate change (including the emerging federal approach to provide "climate services"). Scientific research also underpins the development, implementation, and assessment of policies and technologies intended to limit the magnitude of climate change, and as such is an important partner for technology development programs such a the Climate Change Technology Program (CCTP). Such an "end-to-end," climate change research enterprise was also called for in the recent NRC reports on *Restructuring Federal Climate Research to meet the Challenges of Climate Change* (NRC, 2009l) and *Informing Decisions in a Changing Climate* (NRC, 2009e). Achieving this vision will require high-level coordination, ideally through formal mechanisms, between the research program and action-oriented programs at the federal level. It will also requite new and improved mechanisms for engaging with both research and action-oriented programs at state and local levels. Finally, partnerships with the international research community will be essential for maximizing the effectiveness of domestic investments in climate change research.

Recommendation 7: Congress, federal agencies, and the federal climate change research program should work with other relevant partners (including universities, state and local governments, the international research community, the business community, and other non-governmental organizations) to expand and engage the human capital needed to carry out climate change research and response programs.

The scale, importance, and complexity of the climate challenge implies a critical need to increase the workforce performing fundamental and decision-relevant climate research, implementing responses to climate change, and working at the interface between science and decision making. Thanks to more than three decades of research on climate change, the disciplinary research community in the United States and elsewhere is strong, at least in research areas that have received significant emphasis and support. However, the more integrative and decision-relevant research program described in this report will require expanded intellectual capacity in several previously neglected fields as well as in interdisciplinary research areas. Responding effectively to climate change will also require new interdisciplinary intellectual capacity among state, local, and national government agencies, universities, and other public and private research labs, as well as among science managers coordinating efforts to advance the science of climate change. Building and mobilizing this broad research community will require a concerted and coordinated effort.

The federal climate research program, federal agencies and laboratories, universities, professional societies, and other elements of the nation's research enterprise should use a variety of mechanisms to encourage and facilitate interdisciplinary and integrative research. At the national scale, institutional changes are needed in federal research and mission agencies to increase the focus on interdisciplinary and decision-relevant research throughout government and in the nationwide research efforts the agencies support. Additional venues for presentation and publication of interdisciplinary and decision-relevant climate research are also needed, as well as professional organizations that support and reward these efforts. Finally, state and local governments, corporations, and non-governmental organizations should be key partners in developing and engaging a workforce to implement the national climate research strategy. Further discussion of the actions needed to educate and train future generations of scientists, engineers, technicians, managers, and decision makers for responding to climate change can be found in the companion report *Informing an Effective Response to Climate Change* (NRC, 2010a).

BOX S.1
Statement of Task and Report Overview

The Panel on Advancing the Science of Climate Change, one of five groups convened under the *America's Climate Choices* suite of activities (see Foreword), was charged to address the question: "What can be done to better understand climate change and its interactions with human and ecological systems?" The panel was asked to provide a concise overview of past, present, and future climate change, including its causes and its impacts, then recommend steps to advance our current understanding, including new observations, research programs, next-generation models, and the physical and human assets needed to support these and other activities. The panel was instructed to consider both the natural climate system and the human activities responsible for driving climate change and altering the vulnerability of different regions, sectors, and populations as a single system, and to consider the scientific advances needed to better understand the effectiveness of actions taken to limit the magnitude of future climate change and to adapt to the impacts of climate change (the full statement of task of the Panel on Advancing the Science of Climate Change can be found in Appendix B, and its membership can be found in Appendix C).

In response to this charge, the panel first assessed what science has learned about climate change and its impacts across a variety of sectors, as well as what is known about options for responding to climate change in those sectors. An overview of this analysis is provided in Chapter 2, and the details can be found in the technical chapters (Chapters 6-17) that comprise Part II of the report. The panel also identified scientific advances that could improve our present understanding of climate change or the effectiveness of actions taken to limit its magnitude or adapt to its impacts. Seven cross-cutting research themes, presented in Chapter 4, were identified based on this analysis. Finally, the panel evaluated actions that could be taken to achieve these scientific advances, including the physical and human assets required. Chapter 5 includes the panel's recommendations on these important topics.

PREPUBLICATION COPY

Advancing the Science of Climate Change

America's Climate Choices: Panel on Advancing the Science of Climate Change

Board on Atmospheric Sciences and Climate

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, N.W. • 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 National Oceanic and Atmospheric Administration under contract number DG133R08CQ0062. 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 intelligence community or any of its sub agencies.

International Standard Book Number-XXXX
International Standard Book Number-XXXX

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu

Printed in the United States of America

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. Charles M. Vest 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. Harvey V. Fineberg 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. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

PANEL ON ADVANCING THE SCIENCE OF CLIMATE CHANGE

PAMELA A. MATSON (Chair), Stanford University, California
THOMAS DIETZ (Vice Chair), Michigan State University, East Lansing
WALEED ABDALATI, University of Colorado at Boulder, Colorado
ANTONIO J. BUSALACCHI, JR., University of Maryland, College Park
KEN CALDEIRA, Carnegie Institution of Washington, Stanford, California
ROBERT W. CORELL, H. John Heinz III Center for Science, Economics and the Environment, Washington, D.C.
RUTH S. DEFRIES, Columbia University, New York, New York
INEZ Y. FUNG, University of California, Berkeley
STEVEN GAINES, University of California, Santa Barbara
GEORGE M. HORNBERGER, Vanderbilt University, Nashville, Tennessee
MARIA CARMEN LEMOS, University of Michigan, An Arbor
SUSANNE C. MOSER, Susanne Moser Research & Consulting, Santa Cruz, California
RICHARD H. MOSS, Pacific Northwest National Laboratory, Washington, D.C.
EDWARD A. PARSON, University of Michigan, Ann Arbor
A. R. RAVISHANKARA, National Oceanic and Atmospheric Administration, Boulder, Colorado
RAYMOND W. SCHMITT, Woods Hole Oceanographic Institution, Massachusetts
B. L. TURNER, II, Arizona State University, Tempe
WARREN M. WASHINGTON, National Center for Atmospheric Research, Boulder, Colorado
JOHN P. WEYANT, Stanford University, California
DAVID A. WHELAN, The Boeing Company, Seal Beach, California

NRC Staff:

IAN KRAUCUNAS, Study Director
PAUL STERN, Director, Committee on the Human Dimensions of Global Change
ART CHARO, Senior Program Officer, Space Studies Board
MAGGIE WALSER, Associate Program Officer
KATHERINE WELLER, Research Associate
GYAMI SHRESTHA, Christine Mirzayan Science and Policy Fellow
ROB GREENWAY, Program Associate

Foreword

America's Climate Choices

Convened by the National Research Council in response to a request from Congress (Public Law 110-161), *America's Climate Choices* is a suite of five coordinated activities designed to study the serious and sweeping issues associated with global climate change, including the science and technology challenges involved, and provide advice on the most effective steps and most promising strategies that can be taken to respond.

The *Committee on America's Climate Choices* is responsible for providing overall direction, coordination, and integration of the America's Climate Choices suite of activities and ensuring that these activities provide well-supported, action-oriented, and useful advice to the nation. The Committee convened a *Summit on America's Climate Choices* on March 30-31, 2009 to help frame the study, provide an opportunity for high-level participation and input on key issues, and hear about relevant work carried out by others. The Committee is also charged with writing a final report that builds on four panel reports and other sources to answer the following four overarching questions:

- What short-term actions can be taken to respond effectively to climate change?
- What promising long-term strategies, investments, and opportunities could be pursued to respond to climate change?
- What are the major scientific and technological advances needed to better understand and respond to climate change?
- What are the major impediments (e.g., practical, institutional, economic, ethical, intergenerational, etc.) to responding effectively to climate change, and what can be done to overcome these impediments?

The *Panel on Limiting the Magnitude of Future Climate Change* was charged to describe, analyze, and assess strategies for reducing the net future human influence on climate, including both technology and policy options. The panel's report focuses on actions to reduce domestic greenhouse gas emissions and other human drivers of climate change, such as changes in land use, but also considers the international dimensions of limiting climate change.

The *Panel on Adapting to the Impacts of Climate Change* was charged to describe, analyze, and assess actions and strategies to reduce vulnerability; increase adaptive capacity; improve resiliency; and promote successful adaptation to climate change in different regions, sectors, systems, and populations. The panel's report draws on a wide range of sources and case studies to identify lessons learned from past experiences, promising current approaches, and potential new directions.

The *Panel on Advancing the Science of Climate Change* was charged to provide a concise overview of past, present, and future climate change, including its causes and its impacts, then recommend steps to advance our current understanding, including new observations, research

programs, next-generation models, and the physical and human assets needed to support these and other activities. The panel's report focuses on the scientific advances needed both to improve our understanding of the intergrated human-climate system and to devise more effective responses to climate change.

The *Panel on Informing Effective Decisions and Actions Related to Climate Change* was charged to describe and assess different activities, products, strategies, and tools for informing decision makers about climate change and helping them plan and execute effective, integrated responses. The panel's report describes the different types of climate change-related decisions and actions being taken at various levels and in different sectors and regions; and it develops a framework, tools, and practical advice for ensuring that the best available technical knowledge about climate change is used to inform these decisions and actions.

America's Climate Choices builds on an extensive foundation of previous and ongoing work, including current and past National Research Council reports, assessments from other national and international organizations, the current scientific literature, climate action plans by various entities, and other sources. More than a dozen boards and standing committees of the National Research Council were involved in developing and organizing the study, and many additional groups and individuals provided additional input during the study process. Outside viewpoints and perspectives were also obtained via public events and workshops (including the *Summit*), invited presentations at committee and panel meetings, and comments and questions received through the study website (http://americasclimatechoices.org).

Collectively, the *America's Climate Choices* suite of activities involve more than 90 volunteers from a range of communities including academia, various levels of government, business and industry, other nongovernmental organizations, and the international community. Study participants were charged to write consensus reports that provide broad, action-oriented, and authoritative analyses to inform and guide responses to climate change across the nation. Responsibility for the final content of each report rests solely with the authoring panel and the National Research Council. However, the development of each report included input from and interactions with members of all five study groups; the membership of each group is listed in Appendix A.

Preface

The Panel on Advancing the Science of Climate Change is one of four panels convened under the *America's Climate Choices* suite of activities, which is collectively responsible for providing advice on the most effective steps and most promising strategies that the nation can take to respond to climate change. Our charge was to provide a concise overview of past, present, and future climate change, including its causes and its impacts, then recommend steps to advance our current understanding of climate change and the effectiveness of responses to it (see Appendix B).

The panel's first challenge was to decide how to summarize the large volume of excellent published, peer-reviewed research by the national and international community to produce a concise overview of what is known. We recognize that this report is not brief; we decided that comprehensiveness was essential to the report's credibility. In addition to drawing on the new scientific results being published nearly every week, we were aided in this task by the final U.S. Global Change Research Program (USGCRP) synthesis and assessment product *Global Climate Change Impacts in the United States* (USGCRP, 2009a), the recent National Research Council (NRC) report *Restructuring Federal Research to Meet the Challenges of Climate Change* (NRC, 2009l), and the four volumes of the fourth assessment report by the Intergovernmental Panel on Climate Change (IPCC, 2007a-d). In keeping with the overarching goals of the *America's Climate Choices* study, we focus on the scientific knowledge that we thought would be of greatest interest to decision makers facing crucial choices about how to respond to climate change. Likewise, in looking to the future, we emphasize the scientific advances that could help decision makers identify, evaluate, and implement effective actions to limit its magnitude and adapt to its impacts.

The body of science reviewed by the Panel on Advancing the Science of Climate Change makes a compelling case that climate change is occurring and suggests that it threatens not just the environment and ecosystems of the world but the well-being of people today and in future generations. Climate change is thus a sustainability challenge. We hope that for those who are skeptical or uncertain about what the body of scientific evidence tells us, our report will be informative. The scientific process is never "closed"—new ideas are always part of scientific debate, and there is always more to be learned—but scientific understanding does advance over time as some ideas are supported by multiple lines of evidence while others prove inconsistent with the data or basic principles. Our understanding of climate change and its causes and consequences have advanced in this way.

The panel also examined the adequacy of the science base needed to improve the effectiveness of actions taken to limit the magnitude of future climate change and adapt to its inevitable impacts. Decision makers in the federal government, state governments, tribes, corporations, municipalities, and nongovernmental organizations, as well as citizen decision makers, are beginning to act. Climate research over the past three decades, however, has been driven largely by a need to better understand rather than to explicitly respond to climate change. Until recently, there has been relatively little research focused on the development and implementation of climate-friendly energy sources or land-use practices, socioeconomic and behavioral processes that affect responses, adaptation strategies, analytical approaches to

evaluate tradeoffs and unintended consequences of actions, policy mechanisms, and other response issues. To address the need for new kinds of knowledge, we recommend some significant changes to the nation's climate change research enterprise.

Our report covers a great deal of scientific territory and has been accomplished over a relatively short time period. For this, we thank our tremendously dedicated panel members and remarkably talented NRC study director Ian Kraucunas. The report also benefitted from the insights and assistance of several members of our sister panels and the Committee on America's Climate Choices; in particular, we thank Kris Ebi, George Eads, Bob Fri, Linda Mearns, and Susan Solomon. In addition, we thank Mike Behrenfeld, Bill Nordhaus, Michele Betsill, Peter Schultz, Chris Field, and others who contributed written materials or spoke at panel meetings. We also benefitted from many one-on-one discussions throughout the study process and from the comments and perspectives contributed through the *America's Climate Choices* website. [1]

The report also would not have been possible without the dedication and contributions of the NRC staff. In addition to study director Ian Kraucunas, we thank Paul Stern, who provided many good ideas and written contributions throughout the study; Art Charo, who staffed the workshop on geoengineering held in June 2009; Maggie Walser, who assisted with the panel's response to external review comments; Madeline Woodruff and Joe Casola, who contributed to several chapters; Katie Weller, who compiled the references for the report—a huge job; our science writers/editors Lisa Palmer and Yvonne Baskin; Rob Greenway, who provided logistical support; and Chris Elfring, who provided wise advice at several points in the process.

There is still much to learn about the physical phenomenon of global climate change and its social, economic, and ecological drivers and consequences. There is also a great deal to learn about how to respond effectively without creating serious unintended consequences and, where possible, creating multiple co-benefits. If the scientific progress of the past few decades is any indication, we can expect amazing progress, but only if there is adequate demand, support, and organization for the nation's new era of climate change research.

Pamela Matson, Chair, and Thomas Dietz, Vice-chair
Panel on Adapting to the Impacts of Climate Change

[1] http://americasclimatechoices.org

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 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. We wish to thank the following individuals for their participation in their review of this report:

Doug Arent, National Renewable Energy Laboratory
Donald F. Boesch, University of Maryland
Virginia Burkett, U.S. Geological Survey
Robert Dickinson, The University of Texas at Austin
David Goldston, National Resources Defense Council
Dennis Hartmann, University of Washington
Jeanine A. Jones, California Department of Water Resources
Thomas R. Karl, National Oceanic and Atmospheric Administration
Arthur Lee, ChevronTexaco Corporation, San Ramon
Gerald A. Meehl, National Center for Atmospheric Research
Jerry M. Melillo, Marine Biological Laboratory
William D. Nordhaus, Yale University
Aristides A.N. Patrinos, Synthetic Genomics, Inc.
Ortwin Renn, Institute of Management and Technology
Richard Richels, Electric Power Research Institute, Inc.
Thomas C. Schelling, University of Maryland
Robert H. Socolow, Princeton University
Amanda Staudt, National Wildlife Federation
Michael Toman, The World Bank
John M. Wallace, University of Washington

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **Andrew Solow** (Marine Policy Center) and **Robert Frosch** (Harvard University). Appointed by the National Research Council, 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 committee and the institution.

Institutional oversight for this project was provided by:

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

ANTONIO J. BUSALACCHI, JR. (Chair), University of Maryland, College Park
ROSINA M. BIERBAUM, University of Michigan, Ann Arbor
RICHARD CARBONE, National Center for Atmospheric Research, Boulder, Colorado
WALTER F. DABBERDT, Vaisala, Inc., Boulder, Colorado
KIRSTIN DOW, University of South Carolina, Columbia
GREG S. FORBES, The Weather Channel, Inc., Atlanta, Georgia
ISAAC HELD, National Oceanic and Atmospheric Administration, Princeton, New Jersey
ARTHUR LEE, Chevron Corporation, San Ramon, California
RAYMOND T. PIERREHUMBERT, University of Chicago, Illinois
KIMBERLY PRATHER, Scripps Institution of Oceanography, La Jolla, California
KIRK R. SMITH, University of California, Berkeley
JOHN T. SNOW, University of Oklahoma, Norman
THOMAS H. VONDER HAAR, Colorado State University/CIRA, Fort Collins
XUBIN ZENG, University of Arizona, Tucson

Ex Officio Members

GERALD A. MEEHL, National Center for Atmospheric Research, Boulder, Colorado

NRC Staff

CHRIS ELFRING, Director
LAURIE GELLER, Senior Program Officer
IAN KRAUCUNAS, Senior Program Officer
MARTHA MCCONNELL, Program Officer
MAGGIE WALSER, Associate Program Officer
TOBY WARDEN, Associate Program Officer
JOSEPH CASOLA, Postdoctoral Fellow
RITA GASKINS, Administrative Coordinator
KATIE WELLER, Research Associate
LAUREN M. BROWN, Research Assistant
ROB GREENWAY, Program Associate
SHELLY FREELAND, Senior Program Assistant
AMANDA PURCELL, Senior Program Assistant
JANEISE STURDIVANT, Program Assistant
RICARDO PAYNE, Program Assistant
SHUBHA BANSKOTA, Financial Associate

Contents