

# 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](http://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, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the sponsoring agency.

International Standard Book Number-13: 978-0-309-14588-6 (Book)

International Standard Book Number-10: 0-309-14588-0 (Book)

International Standard Book Number-13: 978-0-309-14589-3 (PDF)

International Standard Book Number-10: 0-309-14589-9 (PDF)

Library of Congress Catalog Control Number: 2010940606

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>

Cover images:

Far left: courtesy of Department of Agriculture/Agricultural Research Service. Photograph by Scott Bauer.

Middle left: Borden, K., and S. Cutter. 2008. Spatial patterns of natural hazards mortality in the United States. *International Journal of Health Geographics* 7 (1):64.

Middle right: Courtesy of DOE/NREL; Credit - Sandia National Laboratories.

Far right: Courtesy of National Oceanic and Atmospheric Administration/Department of Commerce. Photograph by Commander John Bortniak, NOAA Corps, August 1991.

Copyright 2010 by the National Academy of Sciences. All rights reserved.

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](http://www.national-academies.org)

**AMERICA'S CLIMATE CHOICES:  
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

**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, Ann Arbor

**SUSANNE C. MOSER**, Susanne Moser Research & Consulting, Santa Cruz, California

**RICHARD H. MOSS**, Joint Global Change Research Institute (Pacific Northwest National Laboratory/University of Maryland), College Park, Maryland

**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



## 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**, Natural 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 RICHEL**, 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

## ACKNOWLEDGMENTS

---

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

SUMMARY	1
What We Know about Climate Change, 3	
A New Era of Climate Change Research, 5	
Recommendations, 8	
<b>PART I</b>	
1 INTRODUCTION: SCIENCE FOR UNDERSTANDING AND RESPONDING TO CLIMATE CHANGE	19
Scientific Learning About Climate Change, 20	
The New Era of Climate Change Science: Research for Understanding and Responding to Climate Change, 22	
Report Overview, 24	
2 WHAT WE KNOW ABOUT CLIMATE CHANGE AND ITS INTERACTIONS WITH PEOPLE AND ECOSYSTEMS	27
Changes in the Climate System, 29	
Sea Level Rise and the Coastal Environment, 42	
Freshwater Resources, 47	
Ecosystems, Ecosystem Services, and Biodiversity, 51	
Agriculture, Fisheries, and Food Production, 58	
Public Health, 62	
Cities and the Built Environment, 65	
Transportation, 67	
Energy Supply and Use, 70	
Solar Radiation Management, 73	
National and Human Security, 77	
Designing, Implementing, and Evaluating Climate Policies, 80	
3 A NEW ERA OF CLIMATE CHANGE RESEARCH	83
Complexities of Climate Change, 83	
Responding to Climate Risks, 87	
Implications for the Nation's Climate Research Enterprise, 87	



CONTENTS

---

4	INTEGRATIVE THEMES FOR CLIMATE CHANGE RESEARCH	91
	Theme 1: Climate Forcings, Feedbacks, Responses, and Thresholds in the Earth System, 92	
	Theme 2: Climate-Related Human Behaviors and Institutions, 101	
	Theme 3: Vulnerability and Adaptation Analyses of Coupled Human-Environment Systems, 107	
	Theme 4: Research to Support Strategies for Limiting Climate Change, 113	
	Theme 5: Effective Information and Decision-Support Systems, 121	
	Theme 6: Integrated Climate Observing Systems, 126	
	Theme 7: Improved Projections, Analyses, and Assessments, 138	
	Chapter Conclusion, 149	
5	RECOMMENDATIONS FOR MEETING THE CHALLENGE OF CLIMATE CHANGE RESEARCH	151
	An Integrative, Interdisciplinary, Decision-Relevant Research Program, 152	
	Setting Priorities, 155	
	Infrastructural Elements of the Research Program, 158	
	Organizing the Research, 162	
	Broader Partnerships, 171	
	Capacity Building, 177	
	A New Era of Climate Change Research, 180	

**PART II: TECHNICAL CHAPTERS**

6	CHANGES IN THE CLIMATE SYSTEM	183
	Factors Influencing Earth's Climate, 184	
	Observed Climate Change, 201	
	Future Climate Change, 216	
	Research Needs, 228	
7	SEA LEVEL RISE AND THE COASTAL ENVIRONMENT	235
	Observed Sea Level Changes, 236	
	Causes of Sea Level Rise, 238	
	Projections of Future Sea Level Rise, 243	
	Impacts of Sea Level Rise and Other Climate Changes on Coastal Environments, 247	
	Responding to Sea Level Rise, 251	
	Research Needs, 252	

---

8	FRESHWATER RESOURCES	257
	Sensitivity of Freshwater Resources to Climate Change, 258	
	Historical and Future Changes in Freshwater, 259	
	Managing Freshwater in a Changing Climate, 266	
	Research Needs, 267	
9	ECOSYSTEMS, ECOSYSTEM SERVICES, AND BIODIVERSITY	271
	Terrestrial Ecosystems, 273	
	Marine Ecosystems, 280	
	Research Needs, 288	
10	AGRICULTURE, FISHERIES, AND FOOD PRODUCTION	291
	Crop Production, 292	
	Livestock Production, 296	
	Fisheries and Aquaculture Production, 297	
	Science to Support Limiting Climate Change by Modifying Agricultural and Fishery Systems, 300	
	Science to Support Adaptation in Agricultural Systems, 303	
	Food Security, 305	
	Research Needs, 306	
11	PUBLIC HEALTH	309
	Extreme Temperatures and Thermal Stress, 311	
	Severe Weather, 313	
	Infectious Diseases, 314	
	Air Quality, 314	
	Other Health Effects of Climate Change, 317	
	Protecting Vulnerable Populations, 318	
	Research Needs, 319	
12	CITIES AND THE BUILT ENVIRONMENT	323
	Role of Cities in Driving Climate Change, 324	
	Impacts of Climate Change on Cities, 326	
	Science to Support Limiting Future Climate Change, 328	
	Science to Support Adapting to Climate Change, 329	
	Research Needs, 330	

## CONTENTS

---

13	TRANSPORTATION	333
	Role of Transportation in Driving Climate Change, 334	
	Reducing Transportation-Related Greenhouse Gas Emissions, 336	
	Impacts of Climate Change on Transportation, 342	
	Science to Support Adapting to Climate Change in the Transportation Sector, 342	
	Research Needs, 344	
14	ENERGY SUPPLY AND USE	349
	Energy Consumption, 350	
	Reductions in Energy Demand, 352	
	Energy Efficiency Improvements, 353	
	Energy Sources that Reduce Emissions of Greenhouse Gases, 354	
	Carbon Dioxide Removal Approaches, 366	
	Energy Carriers, Transmission, and Storage, 368	
	Science to Support Technology Deployment, 369	
	Likely Impacts of Climate Change on Energy System Operations, 369	
	Science to Support Adapting to Climate Change, 373	
	Research Needs, 374	
15	SOLAR RADIATION MANAGEMENT	377
	History of Solar Radiation Management Proposals, 378	
	Proposed Solar Radiation Management Approaches, 380	
	Possible Unintended Consequences, 382	
	Governance issues, 384	
	Ethical Issues, 384	
	Research Needs, 385	
16	NATIONAL AND HUMAN SECURITY	389
	The Relationship Between Climate and National Security, 392	
	Treaty Verification, 395	
	The Relationship Between Climate and Human Security, 396	
	Research Needs, 398	
17	DESIGNING, IMPLEMENTING, AND EVALUATING CLIMATE POLICIES	401
	Types of Climate Policies and Agreements, 402	
	Research Challenges Associated with Policy Design and Implementation, 406	
	Research Needs, 416	

---

REFERENCES	421
APPENDIXES	
A America's Climate Choices: Membership Lists	475
B Panel on Advancing the Science of Climate Change: Statement of Task	479
C Panel on Advancing the Science of Climate Change: Biographical Sketches	481
D Uncertainty Terminology	491
E The United States Global Change Research Program	493
F Geoengineering Options to Respond to Climate Change: Steps to Establish a Research Agenda (A Workshop to Provide Input to the America's Climate Choices Study)	497
G Acronyms and Initialisms	501

### **Causes of Sea Level Rise**

Past, present, and future changes in global sea level are mainly caused by two fundamental processes: (1) the thermal expansion of the existing water in the world's ocean basins as it absorbs heat and (2) the addition of water from land-based sources—mainly the shrinking of ice sheets and glaciers.

Because of the huge capacity of the oceans to absorb heat, 80 to 90 percent of the heating associated with human GHG emissions over the past 50 years has gone into raising the temperature of the oceans. The subsequent thermal expansion of the oceans is responsible for an estimated 50 percent of the observed sea level rise since the late 19th century. Even if GHG concentrations are stabilized, ocean warming and the accompanying sea level rise will continue until the oceans reach a new thermal equilibrium with the atmosphere. Ice in the world's glaciers and ice sheets contributes directly to sea level rise through melt or the flow of ice into the sea. The major ice sheets of Greenland and Antarctica contain the equivalent of 23 and 197 feet (7 and 60 meters) of sea level, respectively.

### **Projections of Sea Level Rise**

Projections of future sea level have been the subject of active discussion in the recent literature on climate change impacts. The 2007 Assessment Report by the IPCC estimated that sea level would likely rise by an additional 0.6 to 1.9 feet (0.18 to 0.59 meters) by 2100. This projection was based largely on the observed rates of change in ice sheets and projected future thermal expansion over the past several decades and did not include the possibility of changes in ice sheet dynamics. Scientists are working to improve how ice dynamics can be resolved in models. Recent research, including investigations of how sea level responded to temperature variations during the ice age cycles, suggests that sea levels could potentially rise another 2.5 to 6.5 feet (0.8 to 2 meters) by 2100, which is several times larger than the IPCC estimates. However, sea level rise estimates are rather uncertain, due mainly to limits in scientific understanding of glacier and ice sheet dynamics. For instance, recent findings of a warming ocean around Greenland suggest an explanation for the accelerated calving of outlet glaciers into the sea, but the limited data and lack of insight into the mechanisms involved prevent a quantitative estimate of the rate of ice loss at this time. Nevertheless, it is clear that global sea level rise will continue throughout the 21st century due to the GHGs that have already been emitted, that the rate and ultimate amount of sea level rise will be higher if GHG concentrations continue to increase, and that there is a risk of much larger and more rapid increases in sea level. While this risk cannot be quantified