Human-Induced Climate Change
An Interdisciplinary Assessment

Bringing together many of the world's leading experts, this volume is a comprehensive, state-of-the-art review of climate change science, impacts, mitigation, adaptation, and policy. It provides an integrated assessment of research on the key topics that underlie current controversial policy questions.

The first part of the book addresses recent topics and findings related to the physical–biological earth system, including air pollution–climate interactions, climate interactions with the carbon cycle, and quantitative probability estimates of climate sensitivity and change. The next part of the book surveys estimates of the impacts of climate change for different sectors and regions, describes recent studies for individual sectors, and examines how this research might be used in the policy process. The third part examines current topics related to mitigation of greenhouse gases and explores the potential roles of various technological options that would limit greenhouse-gas emissions and enhance terrestrial carbon sinks. The last part focuses on policy design under uncertainty.

Dealing with the scientific, economic, and policy questions at the forefront of the climate change issue, this book will be invaluable for graduate students, researchers, and policymakers interested in all aspects of climate change and the issues that surround it.

Michael E. Schlesinger is Professor of Atmospheric Sciences in the Department of Atmospheric Sciences at the University of Illinois, Urbana-Champaign.

Haroon S. Kheshgi is Program Leader for Global Climate Change Science at ExxonMobil's Corporate Strategic Research.

Joel Smith is a Vice President with Stratus Consulting Inc. in Boulder, Colorado.

Francisco C. de la Chesnaye is Chief of the Climate Economics Branch for the United States Environmental Protection Agency.

John M. Reilly is Associate Director for Research in the Joint Program on the Science and Policy of Global Change, and a Senior Research Scientist in the Laboratory for Energy and Environment at the Massachusetts Institute of Technology.

Tom Wilson is a Technical Executive in the Climate Change Research Program at the Electric Power Research Institute (EPRI).

Charles Kolstad is a Professor in the Department of Economics at the Bren School of Environmental Science and Management, University of California, Santa Barbara.

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Edited by

Michael E. Schlesinger
University of Illinois

Haroon S. Kheshgi
ExxonMobil Research and Engineering

Joel Smith
Stratus Consulting Inc.

Francisco C. de la Chesnaye
US Environmental Protection Agency

John M. Reilly
Massachusetts Institute of Technology

Tom Wilson
Electric Power Research Institute

Charles Kolstad
University of California, Santa Barbara

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UNIVERSITY PRESS

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314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

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Dedication of this book to Alan Manne

During the course of writing this book, the climate community lost one of its greatest treasures. On September 27, 2005 Alan Manne died while doing what he enjoyed most, horseback riding – an activity that he took up when he was 62 and passionately pursued for nearly two decades.

Alan was a gifted modeler who consistently produced ingenious solutions to important problems in both the private and public sectors. When asked to describe the goals of Operations Research, a discipline which he helped to found, he noted, "It is simple; it's doing the best you can with what you have." Adhering to this straightforward but powerful philosophy, he contributed enormously to our understanding of the challenges posed by global climate change, first in deepening our understanding of what would be required to slow the rate of global warming, and then in providing an elegant framework for thinking about benefits and costs.

Born in New York City on May 1, 1925, Alan received a bachelor's degree in economics from Harvard College at the age of 18. After serving in the Navy during the Second World War, he returned to Harvard, where he earned a doctorate in economics in 1950. He stayed on there as an instructor before accepting a position at the Rand Corporation as an economic analyst from 1952 to 1956. He subsequently served as a professor at Harvard, Yale and Stanford Universities, with a brief hiatus as an economist at the International Institute for Applied Systems Analysis in Vienna, Austria. He retired formally from teaching in 1992 when he became professor emeritus in Stanford's Department of Operations Research.

Over four decades, Alan applied economic models internationally, aiding India in developing its fertilizer industry, and developing industrial-resource and planning models for Mexico and Turkey. He also explored the economic consequences surrounding alternative fuels and energy conservation. More recently, he shifted his focus to addressing the risks posed by global climate change.

During his career he received many honors, including being named a fellow of the Econometric Society and the American Academy of Arts and Sciences, Member of the National Academy of Engineering, and recipient of the Larnder Memorial Prize of the Canadian Operations Research Society, Lancaster Prize of the Operations Research Society of America, and the Paul Frankel Award from the US Association of Energy Economists. He also received honorary degrees from Gutenberg University and from the University of Geneva.

Alan's contributions to our understanding of the impacts of human activity on climate extend well beyond his personal research. Over the years, he taught and mentored a generation of students who share his values and high standards. These include those who had the honor to learn from Alan directly in the classroom and through personal collaborations, and the broader community who benefited indirectly through meetings such as the Climate Change Impacts/Integrated Assessment meetings held annually in Snowmass, Colorado, for the past 11 years. As such, it is fitting that this volume be dedicated to Alan, and it is comforting that his work lives on through a new generation of researchers.

No tribute to Alan would be complete without acknowledging the others in the Manne family who provided the warm, gracious, and welcoming environment for so many of Alan's interactions with his colleagues, students, and friends. These include his dear wife Jacqueline, and three children, of whom he was so proud: Edward, Henry, and Elizabeth. His passion and devotion to his family – and theirs to him – were clear to all.

Richard Richels
January 8, 2006

Contents

Contributors

Natalia Andronova
Department of Atmospheric
Oceanic and Space Science
University of Michigan
1541D Space Research Building
2455 Hayward Street Ann Arbor
MI 48109–2143
USA

Paul Bernstein
5265 Lawelawe Pl.
Honolulu
HI 96821
USA

David F. Bradford
(deceased)

Francisco C. de la Chesnaye
Climate Change Division
Office of Atmospheric Programs
US Environmental Protection Agency
1200 Pennsylvania Ave.
NW (6207J) Washington
DC 20460
USA

Benjamin J. DeAngelo
Climate Change Division
Office of Atmospheric Programs
US Environmental Protection Agency
1200 Pennsylvania Ave.
NW (6207J)
Washington
DC 20460
USA

Anthony Del Genio
NASA Goddard Institute for Space Studies
2880 Broadway New York
NY 10025
USA

Casey Delhotal
Climate Change Division
Office of Atmospheric Programs
US Environmental Protection Agency
1200 Pennsylvania Ave.; NW (6207J)
Washington
DC 20460
USA

Suraje Dessai
Tyndall Centre for Climate Change Research
School of Environmental Sciences
University of East Anglia
Norwich NR4 7TJ
UK

James J. Dooley
Pacific Northwest National Laboratory
Joint Global Change Research Institute at the University of Maryland
8400 Baltimore Avenue
Suite 201 College Park
MD 20740–2496
USA

Robert Earle
2125 E. Orange Grove Blvd. Pasadena
CA 91104
USA

Kristie L. Ebi
Exponent Health Group 1800 Diagonal Road
Suite 300 Alexandria
VA 22314
USA

Jae Edmonds
Pacific Northwest National Laboratory
Joint Global Change Research Institute at the University of Maryland
8400 Baltimore Avenue
Suite 201 College Park

MD 20740–2496
USA

Bas Eickhout
Global Sustainability and Climate Team
Netherlands Environmental Assessment Agency (MNP)
PO Box 303
3720 AH Bilthoven A. van Leeuwenhoeklaan 9
Bilthoven
The Netherlands

Benjamin Felzer
Ecosystems Center at the Marine Biological Laboratory
Starr Building
MBL Street
Woods Hole
MA 02543
USA

Brian S. Fisher
ABARE
Edmund Barton Building
Macquarie Street
Barton
ACT 2600 GOP Box 1563
Canberra
ACT 2600, Australia

M. A. Ford
ABARE
Edmund Barton Building
Macquarie Street
Barton
Act 2600 GOP Box 1563
Canberra
ACT 2600, Australia

Julio Friedmann
Lawrence Livermore National Laboratory
7000 East Ave Livermore
CA 94550–9234
USA

Junichi Fujino
National Institute for Environmental Studies
16–2 Onogawa
Tsukuba 305–8506
Japan

Dave Godwin
Stratospheric Protection Division
Office of Atmospheric Programs
US Environmental Protection Agency
1200 Pennsylvania Ave.
NW (6205J) Washington
DC 20460 USA

Jim W. Hall
School of Civil Engineering and Geosciences
University of Newcastle-upon-Tyne Newcastle
NE1 7RU
UK

Jacqueline M. Hamilton
Centre for Marine and Climate Research
Hamburg University
Leuschnerstr. 91
21031 Hamburg
Germany

Tom Hertel
Center for Global Trade Analysis
Purdue University
1145 Krannert Building 403 West State Street
West Lafayette
IN 47907–1145
USA

Monique Hoogwijk
Ecofys B.V.
PO Box 8408
NL-3503 RK
Utrecht
The Netherlands

Mike Hulme
Climatic Research Unit
University of East Anglia
Norwich
NR4 7TJ UK

Henry Jacoby
Joint Program on the Science and Policy of Global Change
Massachusetts Institute of Technology
E40–439 77 Massachusetts Ave.
Cambridge
MA 02139
USA

Atul K. Jain
Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign
105 S. Gregory Street
Urbana
IL 61801
USA

Mikiko Kainuma
Social and Environmental Systems Division
National Institute for Environmental Studies
16–2 Onogawa
Tsukuba 305–8506
Japan

Klaus Keller
208 Deike Building
Department of Geosciences
The Pennsylvania State University
University Park
PA 16802
USA

Haroon S. Kheshgi
ExxonMobil Research and Engineering Company
Route 22 East Annandale
NJ 08801
USA

Seung-Rae Kim
Woodrow Wilson School and Department of Economics
Princeton University
Princeton
NJ 08544
USA

Charles Kolstad
Department of Economics
University of California
Santa Barbara
CA 93106–9210
USA

R. Sari Kovats
Centre on Global Change and Health
London School of Hygiene and Tropical Medicine
Keppel Street
London WC1E 7HT
UK

Akshay S. Kumar
Bowie New Town Center 4201 Northview Drive
Suite 404 Bowie
MD 20716
USA

Huey-Lin Lee
Center for Global Trade Analysis
Purdue University
1145 Krannert Building
403 West State Street
West Lafayette
IN 47907–1145
USA

Rik Leemans
Environmental Systems Analysis Group
Wageningen University and Research (WUR)
PO Box 47
6700 AA Wageningen
The Netherlands

Bin Li
Department of Atmospheric Science
University of Illinois at Urbana-Champaign
105 S. Gregory St.
Urbana
IL 61801
USA

Yun Li
Woodrow Wilson School
Robertson Hall
Princeton University
Princeton
NJ 08544
USA

Alan S. Manne
(deceased)

Toshihiko Masui
National Institute for Environmental Studies
16–2 Onogawa
Tsukuba 305–8506
Japan

Yuzuru Matsuoka
Kyoto University
Kyoto 606–8501
Japan

A. L. Matysek
ABARE
Edmund Barton Building
Macquarie Street
Barton
ACT 2600 GOP Box 1563
Canberra
ACT 2600, Australia

Bruce A. McCarl
Department of Agricultural Economics
Texas A & M University

College Station
TX 77843–2124
USA

Robert Mendelsohn
Yale FES
230 Prospect Street
New Haven
CT 06511
USA

Surabi Menon
Lawrence Berkeley National Laboratory
MS90KR109
1 Cyclotron Road Berkeley
CA 94720
USA

David Montgomery
1201 F St. NW Ste. 700
Washington
DC 20004
USA

Robert J. Nicholls
School of Civil Engineering and the Environment
University of Southampton
Southampton
SO17 1BJ
UK

Michael Oppenheimer
Department of Geosciences
Princeton University
Princeton
NJ 08544
USA

J. D. Opsteegh
KNMI
PO Box 201 De Bilt
3730 AE
The Netherlands

Deborah Ottinger-Schaefer
Climate Change Division
Office of Atmospheric Programs
US Environmental Protection Agency
1200 Pennsylvania Ave.
NW (6207J) Washington
DC 20460
USA

Sergey Paltsev
Joint Program on the Science and Policy of Global Change
Massachusetts Institute of Technology
E40–429
77 Massachusetts Ave. Cambridge
MA 02139
USA

Joyce Penner
1538 Space Research Building
Department of Atmospheric
Oceanic and Space Sciences
University of Michigan
2455 Hayward Street Ann Arbor
MI 48109–2143
USA

Hugh M. Pitcher
Joint Global Change Research Institute
8400 Baltimore Ave.
Suite 201 College Park
MD 20740
USA

Billy Pizer
Resources for the Future
1616 P Street
NW Washington
DC 20036
USA

Ronald Prinn
Department of Earth
Atmosphere
and Planetary Sciences
Massachusetts Institute of Technology
E54–1312 77 Massachusetts Ave.
Cambridge
MA 02139
USA

Navin Ramankutty
SAGE Nelson Institute for Environmental Studies
University of Wisconsin
1710 University Avenue
Madison
WI 53726
USA

John M. Reilly
Joint Program on the Science and Policy of Global Change
Massachusetts Institute of Technology
E40–433
77 Massachusetts Ave. Cambridge
MA 02139
USA

Richard Richels
Electric Power Research Institute
2000 L Street NW
Suite 805 Washington
DC 20036
USA

Steven K. Rose
Climate Change Division
Office of Atmospheric Programs
US Environmental Protection Agency
1200 Pennsylvania Avenue, NW (6207J)
Washington
DC 20460
USA

Leon D. Rotstayn
CSIRO Marine and Atmospheric Research
Aspendale
Vic. 3195 Australia

Benjamin J. Santer
Lawrence Livermore National Laboratory
7000 East Avenue Livermore
CA 94550
USA

Marcus Sarofim
Joint Program on the Science and Policy of Global Change
Massachusetts Institute of Technology
E40–411
77 Massachusetts Ave.
Cambridge
MA 02139
USA

Jayant A. Sathaye
MS 90–4000 Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley
CA 94720
USA

Michiel Schaeffer
Royal Netherlands Embassy
PO Box 20061
2500EB Den Haag
The Netherlands

Michael E. Schlesinger
Department of Atmospheric Science
University of Illinois at Urbana-Champaign
105 S. Gregory St. Urbana
IL 61801
USA

Uwe Schneider
Hamburg University
Centre of Marine and Atmospheric Sciences
Research unit Sustainability and Global Change
Bundesstrasse 55
D-20146 HAMBURG
Germany

Anne E. Smith
CRA International
1201 F Street NW
Suite 700 Washington
DC 20004–1204
USA

Joel Smith
Stratus Consulting Inc.
PO Box 4059
Boulder
CO 80306–4059
USA

Brent Sohngen
AED Economics
Ohio State University
2120 Fyffe Rd. Columbus
OH 43210–1067
USA

Gerald M. Stokes
Joint Global Change Research Institute
8400 Baltimore Ave.
Suite 201
College Park
MD 20740
USA

Bart J. Strengers
Global Sustainability and Climate Team
Netherlands Environmental Assessment Agency (MNP)
PO Box 303
3720 AH Bilthoven
A. van Leeuwenhoeklaan 9 Bilthoven
The Netherlands

James L. Sweeney
Stanford University Terman Engineering Center
Room 440
380 Panama Way
Stanford
CA 94305–4026
USA

Kiyoshi Takahashi
National Institute for Environmental Studies

16–2 Onogawa
Tsukuba 305–8506
Japan

Kok Hou Tay
Blk 21
St. George's Road #20–174 S(321021)
Singapore

Richard S. J. Tol
Hamburg University ZMK
Bundesstrasse 55
20146 Hamburg
Germany

Ferenc Toth
International Atomic Energy Agency
PO Box 100
Wagramer Strasse 5
A-1400 Vienna
Austria

Detlef van Vuuren
Global Sustainability and Climate Team
Netherlands Environmental Assessment Agency (MNP)
PO Box 303
3720 AH Bilthoven A. van Leeuwenhoeklaan 9
Bilthoven
The Netherlands

Chien Wang
Department of Earth
Atmosphere
and Planetary Sciences
Massachusetts Institute of Technology
E40–425 77 Massachusetts Ave.
Cambridge
MA 02139
USA

Minghuai Wang
1546 Space Research Building
Department of Atmospheric
Oceanic and Space Sciences
University of Michigan
2455 Hayward Street Ann Arbor
MI 48109–2143
USA

Mort Webster
217 Abernethy Hall
CB# 3435 Department of Public Policy
The University of North Carolina at Chapel Hill
Chapel Hill
NC 27599–3435
USA

Tom Wigley
National Center for Atmospheric Research
Boulder CO 80307–3000
USA

Larry J. Williams
Global Climate Research
Electric Power Research Institute
3420 Hillview Ave.
Palo Alto
CA 94304–1395
USA

Thomas Wilson
Electric Power Research Institute
3412 Hillview Ave.
PO Box 10412
Palo Alto
CA 94303
USA

Marshall Wise
Pacific Northwest National Laboratory
Joint Global Change Research Institute at the University of Maryland
8400 Baltimore Avenue
Suite 201 College Park
MD 20740–2496
USA

K. Woffenden
ABARE
Edmund Barton Building
Macquarie Street
Barton
ACT 2600 GOP Box 1563
Canberra
ACT 2600 Australia

Gary Yohe
Wesleyan University
238 Church Street
Middletown
CT 06459
USA

Preface

This volume of peer-reviewed chapters arose from a scientific meeting – the Stanford Energy Modeling Forum on Climate Change Impacts/Integrated Assessment (CCI/IA) – that has occurred annually now for 11 years during boreal summer in Snowmass, Colorado, under the leadership and direction of John Weyant. The concept for the CCI/IA meetings was developed by Richard Richels, Jae Edmonds, and Michael Schlesinger in October 1994 at the Third Japan–US Workshop on Global Change at the East–West Center, Honolulu, Hawaii. The objectives of these CCI/IA meetings were to improve: (1) the representation of the impacts of climate change in integrated assessment (IA) models, and (2) IA modeling of the climate-change problem by bringing together disciplinary experts from relevant scientific fields. A planning meeting was held in March 1995 at Dulles Airport. The first CCI/IA meeting was held in summer 1995, and the most recent meeting took place in summer 2005. The CCI/IA meetings have been sponsored by the Electric Power Research Institute, the US Department of Energy, the US Environmental Protection Agency, the US National Oceanographic and Atmospheric Administration, the US National Science Foundation, the Australian Bureau of Agricultural Resource Economics, the ExxonMobil Corporation, the National Institute for Environmental Studies of Japan, and the European Commission.

The initial meeting in 1995 was organized under what turned out to be a rather naïve assumption that the climate-change impact-modeling community would show up and hand off a set of damage functions to the integrated assessment modelers, and then the two groups could part and continue on their independent research paths. What resulted instead was a rich, sometimes heated, interchange among the two communities. From the perspective of an integrated assessment modeler, the IA community learned much about the complexities of representing climate impacts and saw the need to learn much more.

Eleven years and eleven meetings later we are far better informed, even if the representation of impacts of climate change in our integrated assessment models remains nascent. Models are always a simplification of the real-world processes they hope to represent. Understanding better the full complexity of systems, even if it is not possible to represent all this complexity in a model, can lead to more intelligent use of models and results because one is better able to describe the caveats, limits, and possible biases and omissions. Rather than a hand-off of results, the annual meeting has become instead an intensive set of tutorials for integrated assessment modelers, bringing together top scientists and economists who describe recent advances in their fields and in so doing challenge the integrated assessment community to represent these processes in their models. The very nature of the meeting and research is interdisciplinary.

Where does disciplinary research end and integrated assessment begin? Fortunately, the answer to this question has blurred as integrated assessment modeling has matured. In representing interactions between complex systems, these models provide new scientific research results and insights that cannot be demonstrated with component models run alone. They have become more than simple assessment tools. At the same time, these new findings have stretched the Earth system modeling community to more fully integrate human systems. The organization of this volume reflects the research approach of the community, juxtaposing results and chapters from some of the more complete integrated assessment models with results from more detailed models of one or a few components of the full Earth system.

Part I of the volume, **Climate system science**, addresses new topics and findings related to the physical–biological Earth system. Several chapters examine interactions between air pollution and climate including the roles of aerosols and tropospheric ozone. Another set focus on climate interactions with the carbon cycle, including chapters on land use, the biosphere, and emissions time paths in stabilization regimes. Finally, a recurring theme throughout the volume is uncertainty, represented in this section by chapters that have tried to establish quantitative probability estimates of climate sensitivity and change.

Part II of the volume, **Impacts and adaptation**, addresses the original focus of the Snowmass meetings. Chapters range from surveys that pull together estimates for different sectors and regions to provide a comprehensive evaluation of climate damages, to new studies and reviews for individual sectors ranging from water and agriculture, ecosystems and biodiversity, health, coastal effects of sea-level rise, and effects on tourism. Also included are chapters that address

how this research might be used in the policy process, whether that relates to avoiding "dangerous interference" in the climate system, the key goal of the Framework Convention on Climate Change, or the more on-the-ground problem of working with planning ministries to improve the adaptive capacity of vulnerable people and activities.

Part III, **Mitigation of greenhouse gases**, addresses current topics related to mitigation of greenhouse gases. These chapters deal with the potential roles of various technological options that would limit greenhouse gas emissions, ranging from carbon dioxide capture and storage, to hydrogen systems to improvements in energy efficiency. Chapters cover options for reducing non-CO_2 greenhouse gases, and the potential for enhancing terrestrial carbon sinks. Also within this section are chapters that address the role of expectations and technical issues that arise in evaluating the costs of mitigation measures, and that draw on lessons from monetary policy on how to set policy under uncertainty.

Finally, Part IV **Policy design and decisionmaking under uncertainty**, is devoted to issues related to the design of mitigation policy. These chapters often draw on formal methods developed to deal with decisionmaking under uncertainty, including the acquisition of information to reduce uncertainty. They consider issues of communicating risk and uncertainty as well as issues of international and domestic policy design.

The volume as a whole provides a solid overview of research on key topics that underlay currently controversial policy questions, addressing these topics using different approaches. It succeeds in addressing topics of interest to the technical modeling community, providing new results of interest to the policy community, and in offering an overview of the rapidly developing field of integrated assessment modeling. It has been our pleasure to attend nearly all of the Snowmass meetings and have the opportunity to interact with the fantastic group of scientists that assemble each summer. We hope this volume conveys much of the excitement and vitality of the community to those who have, at least so far, not been able to attend this workshop, and in so doing encourages the next generation of researchers to join us in this endeavor.