

Climate Change 2007

The Physical Science Basis

The Intergovernmental Panel on Climate Change (IPCC) was set up jointly by the World Meteorological Organization and the United Nations Environment Programme to provide an authoritative international statement of scientific understanding of climate change. The IPCC's periodic assessments of the causes, impacts and possible response strategies to climate change are the most comprehensive and up-to-date reports available on the subject, and form the standard reference for all concerned with climate change in academia, government and industry worldwide. Through three working groups, many hundreds of international experts assess climate change in this Fourth Assessment Report. The Report consists of three main volumes under the umbrella title *Climate Change 2007*, all available from Cambridge University Press:

Climate Change 2007 - The Physical Science Basis

Contribution of Working Group I to the Fourth Assessment Report of the IPCC
(ISBN 978 0521 88009-1 Hardback; 978 0521 70596-7 Paperback)

Climate Change 2007 - Impacts, Adaptation and Vulnerability

Contribution of Working Group II to the Fourth Assessment Report of the IPCC
(978 0521 88010-7 Hardback; 978 0521 70597-4 Paperback)

Climate Change 2007 - Mitigation of Climate Change

Contribution of Working Group III to the Fourth Assessment Report of the IPCC
(978 0521 88011-4 Hardback; 978 0521 70598-1 Paperback)

Climate Change 2007 - The Physical Science Basis is the most comprehensive and up-to-date scientific assessment of past, present and future climate change. The report provides:

- the most complete and quantitative assessment of how human activities are affecting the radiative energy balance in the atmosphere
- a more extensive assessment of changes observed throughout the climate system than ever before using the latest measurements covering the atmosphere, land surface, oceans, and snow, ice and frozen ground
- a detailed assessment of past climate change and its causes
- the first probabilistic assessment of climate model simulations and projections using detailed atmosphere-ocean coupled models from 18 modelling centres around the world
- a detailed assessment of climate change observations, modelling, and attribution for every continent

Simply put, this latest assessment of the IPCC will again form the standard scientific reference for all those concerned with climate change and its consequences, including students and researchers in environmental science, meteorology, climatology, biology, ecology and atmospheric chemistry, and policy makers in governments and industry worldwide.

From reviews of the Third Assessment Report – Climate Change 2001:

‘The detail is truly amazing ... invaluable works of reference ... no reference or science library should be without a set [of the IPCC volumes] ... unreservedly recommended to all readers.’

Journal of Meteorology

‘This well-edited set of three volumes will surely be the standard reference for nearly all arguments related with global warming and climate change in the next years. It should not be missing in the libraries of atmospheric and climate research institutes and those administrative and political institutions which have to deal with global change and sustainable development.’

Meteorologische Zeitschrift

‘... likely to remain a vital reference work until further research renders the details outdated by the time of the next survey ... another significant step forward in the understanding of the likely impacts of climate change on a global scale.’

International Journal of Climatology

‘The IPCC has conducted what is arguably the largest, most comprehensive and transparent study ever undertaken by mankind ... The result is a work of substance and authority, which only the foolish would deride.’

Wind Engineering

‘... the weight of evidence presented, the authority that IPCC commands and the breadth of view can hardly fail to impress and earn respect. Each of the volumes is essentially a remarkable work of reference, containing a plethora of information and copious bibliographies. There can be few natural scientists who will not want to have at least one of these volumes to hand on their bookshelves, at least until further research renders the details outdated by the time of the next survey.’

The Holocene

‘The subject is explored in great depth and should prove valuable to policy makers, researchers, analysts, and students.’

American Meteorological Society

From reviews of the Second Assessment Report – Climate Change 1995:

‘... essential reading for anyone interested in global environmental change, either past, present or future. ... These volumes have a deservedly high reputation’

Geological Magazine

‘... a tremendous achievement of coordinating the contributions of well over a thousand individuals to produce an authoritative, state-of-the-art review which will be of great value to decision-makers and the scientific community at large ... an indispensable reference.’

International Journal of Climatology

‘... a wealth of clear, well-organized information that is all in one place ... there is much to applaud.’

Environment International

Climate Change 2007

The Physical Science Basis

Edited by

Susan Solomon

Co-Chair,
IPCC Working Group I

Dahe Qin

Co-Chair,
IPCC Working Group I

Martin Manning

Head, Technical Support Unit
IPCC Working Group I

Melinda Marquis

Kristen Averyt

Melinda M.B. Tignor

Henry LeRoy Miller, Jr.

Technical Support Unit, IPCC Working Group I

Zhenlin Chen

China Meteorological Administration

Contribution of Working Group I
to the Fourth Assessment Report of the
Intergovernmental Panel on Climate Change

Published for the Intergovernmental Panel on Climate Change

 **CAMBRIDGE**
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press

32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org

Information on this title: www.cambridge.org/9780521880091

© Intergovernmental Panel on Climate Change 2007

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2007

Printed in Canada by Friesens

A catalog record for this publication is available from the British Library.

ISBN 978-0-521-88009-1 hardback

ISBN 978-0-521-70596-7 paperback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party Internet Web sites referred to in this publication and does not guarantee that any content on such Web sites is, or will remain, accurate or appropriate.

Please use the following reference to the whole report:

IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Cover photo:

The Blue Marble western and eastern hemispheres. These images integrate land, ocean, sea ice and clouds into a visual representation of the earth's climate system. They are based on space-borne earth observation data from NASA's MODIS (MODerate resolution Imaging Spectroradiometer) sensor aboard the TERRA and AQUA satellites. These images are part of the Blue Marble dataset which is freely available at <http://bluemarble.nasa.gov>. They are further documented in Stöckli, R., Vermote, E., Saleous, N., Simmon, R., and Herring, D. (2006). True color earth data set includes seasonal dynamics. EOS, 87(5):49, 55.

Foreword

Representing the first major global assessment of climate change science in six years, “Climate Change 2007 – The Physical Science Basis” has quickly captured the attention of both policymakers and the general public. The report confirms that our scientific understanding of the climate system and its sensitivity to greenhouse gas emissions is now richer and deeper than ever before. It also portrays a dynamic research sector that will provide ever greater insights into climate change over the coming years.

The rigor and credibility of this report owes much to the unique nature of the Intergovernmental Panel on Climate Change (IPCC). Established by the World Meteorological Organization and the United Nations Environment Programme in 1988, the IPCC is both an intergovernmental body and a network of the world’s leading climate change scientists and experts.

The chapters forming the bulk of this report describe scientists’ assessment of the state-of-knowledge in their respective fields. They were written by 152 coordinating lead authors and lead authors from over 30 countries and reviewed by over 600 experts. A large number of government reviewers also contributed review comments.

The Summary for Policymakers was approved by officials from 113 governments and represents their understanding – and their ownership – of the entire underlying report. It is this combination of expert and government review that constitutes the strength of the IPCC.

The IPCC does not conduct new research. Instead, its mandate is to make policy-relevant – as opposed to policy-prescriptive – assessments of the existing worldwide literature on the scientific, technical and socio-economic aspects of climate change. Its earlier assessment reports helped to inspire governments to adopt and implement the United Nations Framework Convention on Climate Change and the Kyoto Protocol. The current report will also be highly relevant as Governments consider their options for moving forward together to address the challenge of climate change.

Climate Change 2007 – the Physical Science Basis is the first volume of the IPCC’s Fourth Assessment Report. The second volume considers climate change impacts, vulnerabilities and adaptation options, while the third volume assesses the opportunities for and the costs of mitigation. A fourth volume provides a synthesis of the IPCC’s overall findings.

The Physical Science Basis was made possible by the commitment and voluntary labor of the world’s leading climate scientists. We would like to express our gratitude to all the Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors and Reviewers. We would also like to thank the staff of the Working Group I Technical Support Unit and the IPCC Secretariat for their dedication in coordinating the production of another successful IPCC report.

Many Governments have supported the participation of their resident scientists in the IPCC process and contributed to the IPCC Trust Fund, thus also assuring the participation of experts from developing countries and countries with economies in transition. The governments of Italy, China, New Zealand and Norway hosted drafting sessions, while the Government of France hosted the final plenary that approved and accepted the report. The Government of the United States of America funded the Working Group I Technical Support Unit.

Finally, we would like to thank Dr R.K. Pachauri, Chairman of the IPCC, for his sound direction and tireless and able guidance of the IPCC, and Dr. Susan Solomon and Prof. Dahe Qin, the Co-Chairs of Working Group I, for their skillful leadership of Working Group I through the production of this report.



M. Jarraud
Secretary General
World Meteorological Organization



A. Steiner
Executive Director
United Nations Environment Programme

Preface

This Working Group I contribution to the IPCC's Fourth Assessment Report (AR4) provides a comprehensive assessment of the physical science of climate change and continues to broaden the view of that science, following on from previous Working Group I assessments. The results presented here are based on the extensive scientific literature that has become available since completion of the IPCC's Third Assessment Report, together with expanded data sets, new analyses, and more sophisticated climate modelling capabilities.

This report has been prepared in accordance with rules and procedures established by the IPCC and used for previous assessment reports. The report outline was agreed at the 21st Session of the Panel in November 2003 and the lead authors were accepted at the 31st Session of the IPCC Bureau in April 2004. Drafts prepared by the authors were subject to two rounds of review and revision during which over 30,000 written comments were submitted by over 650 individual experts as well as by governments and international organizations. Review Editors for each chapter have ensured that all substantive government and expert review comments received appropriate consideration. The Summary for Policymakers was approved line-by-line and the underlying chapters were then accepted at the 10th Session of IPCC Working Group I from 29 January to 1 February 2007.

Scope of the Report

The Working Group I report focuses on those aspects of the current understanding of the physical science of climate change that are judged to be most relevant to policymakers. It does not attempt to review the evolution of scientific understanding or to cover all of climate science. Furthermore, this assessment is based on the relevant scientific literature available to the authors in mid-2006 and the reader should recognize that some topics covered here may be subject to further rapid development.

A feature of recent climate change research is the breadth of observations now available for different components of the climate system, including the atmosphere, oceans, and cryosphere. Additional observations and new analyses have broadened our understanding and enabled many uncertainties to be reduced. New information has also led to some new questions in areas such as unanticipated changes in ice sheets, their potential effect on sea level rise, and the implications of complex interactions between climate change and biogeochemistry.

In considering future projections of climate change, this report follows decisions made by the Panel during the AR4 scoping and approval process to use emission scenarios that have been previously assessed by the IPCC for consistency across the three Working Groups. However, the value of information from new climate models related to climate stabilization has also been recognized. In order to address both topics, climate modelling groups have conducted climate simulations that included idealized experiments in which atmospheric composition is held constant. Together with climate model ensemble simulations, including many model runs for the 20th and 21st centuries, this assessment has been able to consider far more simulations than any previous assessment of climate change.

The IPCC assessment of the effects of climate change and of options for responding to or avoiding such effects, are assessed by Working Groups II and III and so are not covered here. In particular, while this Working Group I report presents results for a range of emission scenarios consistent with previous reports, an updated assessment of the plausible range of future emissions can only be conducted by Working Group III.

The Structure of this Report

This Working Group I assessment includes, for the first time, an introductory chapter, Chapter 1, which covers the ways in which climate change science has progressed, including an overview of the methods used in climate change science, the role of climate models and evolution in the treatment of uncertainties.

Chapters 2 and 7 cover the changes in atmospheric constituents (both gases and aerosols) that affect the radiative energy balance in the atmosphere and determine the Earth's climate. Chapter 2 presents a perspective based on observed change in the atmosphere and covers the central concept of radiative forcing. Chapter 7 complements this by considering the interactions between the biogeochemical cycles that affect atmospheric constituents and climate change, including aerosol/cloud interactions.

Chapters 3, 4 and 5 cover the extensive range of observations now available for the atmosphere and surface, for snow, ice and frozen ground, and for the oceans respectively. While observed changes in these components of the climate system are closely inter-related through physical processes, the separate chapters allow a more focused assessment of available data and their uncertainties, including remote sensing data from satellites. Chapter 5 includes observed changes in sea level, recognizing the strong interconnections between these and ocean heat content.

Chapter 6 presents a palaeoclimatic perspective and assesses the evidence for past climate change and the extent to which that is explained by our present scientific understanding. It includes a new assessment of reconstructed temperatures for the past 1300 years.

Chapter 8 covers the ways in which physical processes are simulated in climate models and the evaluation of models against observed climate, including its average state and variability. Chapter 9 covers the closely related issue of the extent to which observed climate change can be attributed to different causes, both natural and anthropogenic.

Chapter 10 covers the use of climate models for projections of global climate including their uncertainties. It shows results for different levels of future greenhouse gases, providing a probabilistic assessment of a range of physical climate system responses and the time scales and inertia associated with such responses. Chapter 11 covers regional climate change projections consistent with the global projections. It includes an assessment of model reliability at regional levels and the factors that can significantly influence regional scale climate change.

The Summary for Policymakers (SPM) and Technical Summary (TS) of this report follow a parallel structure and each includes cross references to the chapter and section where the material being summarized can be found in the underlying report. In this way these summary components of the report provide a road-map to the content of the entire report and the reader is encouraged to use the SPM and TS in that way.

An innovation in this report is the inclusion of 19 Frequently Asked Questions, in which the authors provide scientific answers to a range of general questions in a form that will be useful for a broad range of teaching purposes. Finally the report is accompanied by about 250 pages of supplementary material that was reviewed along with the chapter drafts and is made available on CDROM and in web-based versions of the report to provide an additional level of detail, such as results for individual climate models.

Some key policy-relevant questions and issues addressed in this report and the relevant chapters

Question	Chapters
How has the science of climate change advanced since the IPCC began?	1
What is known about the natural and anthropogenic agents that contribute to climate change, and the underlying processes that are involved?	2, 6, 7
How has climate been observed to change during the period of instrumental measurements?	3, 4, 5
What is known of palaeoclimatic changes, before the instrumental era, over time scales of hundreds to millions of years, and the processes that caused them?	6, 9
How well do we understand human and natural contributions to recent climate change, and how well can we simulate changes in climate using models?	8, 9
How is climate projected to change in the future, globally and regionally?	10, 11
What is known about past and projected changes in sea level, including the role of changes in glaciers and ice sheets?	4, 5, 6, 10
Are extremes such as heavy precipitation, droughts, and heat waves changing and why, and how are they expected to change in the future?	3, 5, 9, 10, 11

Acknowledgments

This assessment has benefited greatly from the very high degree of co-operation that exists within the international climate science community and its coordination by the World Meteorological Organization World Climate Research Program (WCRP) and the International Geosphere Biosphere Program (IGBP). In particular we wish to acknowledge the enormous commitment by the individuals and agencies of 14 climate modelling groups from around the world, as well as the archiving and distribution of an unprecedented amount (over 30 Terabytes) of climate model output by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). This has enabled a more detailed comparison among current climate models and a more comprehensive assessment of the potential nature of long term climate change than ever before.

We must emphasise that this report has been entirely dependent on the expertise, hard work, and commitment to excellence shown throughout by our Coordinating Lead Authors and Lead Authors with important help by many Contributing Authors. In addition we would like to express our sincere appreciation of the work carried out by the expert reviewers and acknowledge the value of the very large number of constructive comments received. Our Review Editors have similarly played a critical role in assisting the authors to deal with these comments.

The Working Group I Bureau, Kansri Boonpragob, Filippo Giorgi, Bubu Jallow, Jean Jouzel, Maria Martelo and David Wratt have played the role of an editorial board in assisting with the selection of authors and with guiding the initial outline of the report. They have provided

constructive support to the Working Group Co-Chairs throughout for which we are very grateful.

Our sincere thanks go to the hosts and organizers of the four lead author meetings that were necessary for the preparation of the report and we gratefully acknowledge the support received from governments and agencies in Italy, China, New Zealand and Norway. The final Working Group I approval session was made possible by Mr Marc Gillet through the generosity of the government of France and the session was greatly facilitated by Francis Hayes, the WMO Conference Officer.

It is a pleasure to acknowledge the tireless work of the staff of the Working Group I Technical Support Unit, Melinda Marquis, Kristen Averyt, Melinda Tignor, Roy Miller, Tahl Kestin and Scott Longmore, who were ably assisted by Zhenlin Chen, Barbara Keppler, MaryAnn Pykkonen, Kyle Terran, Lelani Arris, and Marilyn Anderson. Graphics support and layout by Michael Shibao and Paula Megenhardt is gratefully appreciated. We thank Reto Stockli for kindly providing images of the Earth from space for the cover of this report. Assistance in helping the Co-Chairs to organize and edit the Frequently Asked Questions by David Wratt, David Fahey, and Susan Joy Hassol, is also appreciated. We should also like to thank Renate Christ, Secretary of the IPCC, and Secretariat staff Jian Liu, Rudie Bourgeois, Annie Courtin and Joelle Fernandez who provided logistical support for government liaison and travel of experts from developing countries and transitional economy countries.

Rajendra K. Pachauri
IPCC Chairman

Susan Solomon
IPCC WGI Co-Chair

Dahe Qin
IPCC WGI Co-Chair

Martin Manning
IPCC WGI TSU Head

Contents

Foreword	v
Preface	vii
Summary for Policymakers	1
Technical Summary	19
1 Historical Overview of Climate Change Science	93
2 Changes in Atmospheric Constituents and Radiative Forcing	129
3 Observations: Atmospheric Surface and Climate Change	235
4 Observations: Changes in Snow, Ice and Frozen Ground	337
5 Observations: Ocean Climate Change and Sea Level	385
6 Palaeoclimate	433
7 Coupling Between Changes in the Climate System and Biogeochemistry	499
8 Climate Models and their Evaluation	589
9 Understanding and Attributing Climate Change	663
10 Global Climate Projections	747
11 Regional Climate Projections	847
Annex I: Glossary	941
Annex II: Contributors to the IPCC WGI Fourth Assessment Report	955
Annex III: Reviewers of the IPCC WGI Fourth Assessment Report	969
Annex IV: Acronyms	981
Index	989

