Climate Change and Climate Modeling

The modeling of past, present and future climates is of fundamental importance to the issue of climate change and variability. *Climate Change and Climate Modeling* provides a solid foundation for science students in all disciplines for our current understanding of global warming and important natural climate variations such as El Niño, and lays out the essentials of how climate models are constructed.

As issues of climate change and impacts of climate variability become increasingly important, climate scientists must reach out to science students from a range of disciplines. Climate models represent one of our primary tools for predicting and adapting to climate change. An understanding of their strengths and limitations – and of what aspects of climate science are well understood and where quantitative uncertainties arise – can be communicated very effectively to students from a broad range of the sciences. This book will provide a basis for students to make informed decisions concerning climate change, whether they go on to study atmospheric science at a higher level or not. The book has been developed over a number of years from the course that the author teaches at UCLA. It has been extensively class-tested by hundreds of students, and assumes no previous background in atmospheric science except basic calculus and physics.

This book:

- provides a solid understanding of the physical climate system and the underpinnings of current climate assessments
- provides a bridge between introductory textbooks and popular science books on climate change, and advanced textbooks on atmospheric science
- is supported by a range of internet resources.

J. David Neelin is a professor and chair of the Department of Atmospheric and Oceanic Sciences, and member of the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles. He has published over 100 scientific papers, including contributions to understanding and predictability of the El Niño/Southern Oscillation phenomenon, decadal variability, vegetation interaction with climate variability, how rainfall interacts with natural climate variability and anthropogenic change, and methods of improving representation of rainfall processes in climate models. He has taught courses in climate science from introductory undergraduate to advanced graduate level. He is a fellow of the John Simon Guggenheim Memorial Foundation, the Royal Meteorological Society and the American Meteorological Society, and the recipient of a Presidential Young Investigator Award, National Science Foundation Special Creativity Award and the American Meteorological Society Meisinger Award.

"This is a timely and important book that lucidly and engagingly covers topics related to climate change, topics that currently receive enormous attention and that unfortunately cause polarization."

Professor S. George Philander, *Princeton University*

"David Neelin's book is a very valuable and accessible textbook for students of climate science, and all those with an interest in climate modeling. It is a thorough and highly readable book that neatly spans the gap between general interest climate change texts and higher-level books for specialists."

Dr Drew Shindell, *NASA Goddard Institute for Space Studies*

"This book presents the diverse subjects of climate modeling and climate variability in a way that is clear and understandable to students from different backgrounds. The author is a world-famous climate scientist who has been highly successful both in research and teaching, covering all of the theoretical, modeling and data analysis aspects of climate science. The book is based on a course he has been teaching at UCLA for many years, which has been extremely popular and highly valued by students from a variety of disciplines. I am sure that the book will soon become the standard textbook on climate modeling and climate change."

Professor Akio Arakawa, *University of California, Los Angeles*

"If you're looking for an up-to-date text that deals with the science of climate change and climate modelling in a way that is both rigorous and accessible, then this book is for you. This timely treatment of a vitally important topic presents a novel integration of climate system science, including variability and change, with the fundamental principles of climate modelling and its applications that is accurate, informative and useful in a range of contexts. The book is structured to provide engaging material for both those interested in engaging with the complex science of climate change, and those whose focus is on developing a broader understanding to apply in areas such as ecology, engineering or policy. Neelin's book will be a valuable addition to my library and mandatory reading for my students."

Dr Janette Lindesay, *Australian National University*

"With the looming prospect of serious climate change at hand, it is ever more important to interest the best and brightest minds in the challenging problems of climate science. But those of us who teach climate science have been handicapped by the lack of a comprehensive and engaging text. With his masterful Climate Change and Climate Modeling, David Neelin has answered our prayers."

Professor Kerry A. Emanuel, *Massachusetts Institute of Technology*

Climate Change and Climate Modeling

J. DAVID NEELIN
University of California, Los Angeles

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521602433

First published 2011
4th printing 2015

Printed in the United Kingdom by T. J. International Ltd, Padstow Cornwall

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

Library of Congress Cataloging in Publication data
Neelin, J. David.
Climate change and climate modeling / J. David Neelin.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-521-84157-3 (hardback) – ISBN 978-0-521-60243-3 (pb)
1. Climatology–Textbooks. 2. Climatic changes–Textbooks. I. Title.
QC861.3.N44 2010
551.6–dc22 2010039193

ISBN 978-0-521-84157-3 Hardback
ISBN 978-0-521-60243-3 Paperback

Additional resources for this publication at www.cambridge.org/neelin

To my parents, who gave me the Earth, and to my kids, who will inherit it.

Contents

Preface

Climate change and climate variability have become important topics in atmospheric, oceanic and environmental sciences. Recent developments in understanding, modeling and prediction of El Niño have brought seasonal-to-interannual climate predictions into everyday life. Projections of global warming as a consequence of human activity have been in the public consciousness for some time, even if the understanding of the scientific issues may not be as deep as would be desirable. There is a need to prepare science students for participation in environmental decision making by teaching the physics of the phenomena and the physical basis of computational climate models. This text aims to teach students current scientific understanding of global warming and of important natural climate variations such as El Niño, while laying out the essentials of how climate models are constructed.

Most of these students are not likely to become climate model builders. Some may become users of climate model output, others simply need to be aware of the strengths and limitations of climate modeling. Thus a course need not be so specialized that it aims only at future climate modelers, but should be at a level where some science background can be assumed. The treatment does not shy away from writing down the equations for a climate model, but they are explained in a way that students with calculus for biologists as a background have no trouble following.

This book arises from a course I have taught and continuously revised over the past dozen years at UCLA. It serves (i) as an initial core course for majors in Atmospheric, Oceanic and Environmental Sciences, and an option in the Environmental Sciences major; and (ii) as an introduction to this field for majors in other science fields, notably biology, with some students from social sciences and engineering. The second group is more numerous and reaching out to them has greatly increased the undergraduate population served by our upper division classes. The course grew from a handful of students initially until it routinely hit the enrollment cap with as many as 90 students. The mixture of students works well once a little extra background is provided for non-majors; typically the highest grade in the class goes to a non-major.

Climate science has grown too large to be fully treated in a single course, and this text reflects its origins as part of a larger curriculum. Following growth of the course on which this textbook is based, our department developed further courses for the upper division science audience, including courses on paleoclimate and biogeochemical cycles, atmospheric chemistry, and oceanography. As a result, certain topics related to these areas are treated briefly here. It seems likely that a similar sequence can reach across departmental boundaries at other universities. However, for an instructor planning an all-in-one course, other resources exist to extend the areas abbreviated here. If a shorter treatment of the physical climate system is desired, this book is written so that certain pieces can be condensed in a modular manner. For instance, Chapters 3 and 5 each have a summary section that assists abbreviation (sections 3.8 and 5.1, respectively). Chapter 5 can be treated succinctly with sections 5.1, 5.4 and 5.5, while still covering essentials of climate models, their evaluation and sources of error. Section 4.6 can be skipped or skimmed for a shorter treatment of El Niño that still captures the bottom line for forecasts and impacts.

Endnotes for each chapter are used to provide more rigorous underpinning and connection to the research literature. These are aimed largely at advanced students and instructors. In some cases the endnotes are used to provide definitions or elaborations that would weigh down the text.

The text sticks to the science of these issues and does not directly address policy questions, following the traditional approach that climate science should provide the best available information for policy decisions, but maintain reserve with respect to advocacy. Topics that follow the news cycle change too much from year to year to be suitable material for a textbook, but the background provided here can aid in discussing some of these as they arise. For instance, a recurring suggestion that possible warming on Pluto might be relevant to earthly climate change affords students an opportunity to assess this for themselves with the material in Chapter 2 and the information that Pluto has a 249-year, highly elliptical orbit. Substantial effort is made to provide students with a sense of where real uncertainties or limitations of climate models arise, including climatological simulations in Chapter 5, global climate sensitivity in Chapter 6 and 7, and regional sensitivity in Chapter 7. No one is more humble before the complexities of the climate system than the climate modeler trying to improve his or her model's simulation of rainfall in a particular region, or making real-time forecasts of climate variations. The students leave the course with a more concrete understanding of the capabilities and challenges of climate modeling.

Acknowledgments must begin with Joyce Meyerson, whom I first met when she was a student in the climate modeling course, and who has become a key member of my research group, assisting in innumerable ways. The extensive set of illustrations based on a combination of material from the scientific literature, material developed from scientific presentations, and schematics to illustrate key points attests to her skill at taking a scribbled sketch or description and turning it into a clear and aesthetic scientific illustration. This has offered the opportunity to redo even traditional figures, such as ocean current systems, with updates from more recent data. Grayscale versions of figures are included in the text because of a student preference for low cost but color versions and associated PowerPoint presentations are available for all figures online, as are examples of problem set and exam questions. Climate science changes rapidly, tending to leave textbooks behind, so updates to these online materials will be made periodically.

Thanks to former students from the course B. Tang, T. Rippeon, K. Roy, S. Chin, J. Park and others who have contributed corrections or pointed out areas that needed clarification, and to all of my former teaching assistants. Comments from D. Waliser, who has taught from a draft version, and from K. Hales, C. Chou and H. Su are appreciated. For discussion, I thank I. Held, G. Philander, all my UCLA colleagues, and many others. Of the many sources noted in the text I would particularly like to acknowledge a graduate-level volume edited by K. Trenberth, and the reports of the Intergovernmental Panel on Climate Change. To any colleagues whose work is not sufficiently referenced, my apologies – despite a substantial

bibliography, some important work is bound to be left out and references are weighted towards works that summarize parts of the literature, are associated with figures, or are from areas where I have less direct expertise. Federal grants from the National Oceanographic and Atmospheric Administration, the National Aeronautics and Space Administration, and the National Science Foundation have supported my research over the years. Aspects of the preparation of the course and of material for this textbook have formed part of the contributions to undergraduate education and outreach of my National Science Foundation grant. A fellowship from the John Simon Guggenheim Memorial Foundation contributed to completion of this work.