Physics of the Atmosphere and Climate

Murry Salby's new book provides an integrated treatment of the processes controlling the Earth-atmosphere system developed from first principles through a balance of theory and applications. This book builds on Salby's previous book *Fundamentals of Atmospheric Physics*. The scope has been expanded to include climate, while streamlining the presentation for undergraduates in science, mathematics, and engineering. Advanced material, suitable for graduate students and researchers, has been retained but distinguished from the basic development. The book offers a conceptual yet quantitative understanding of the controlling influences integrated through theory and major applications. It leads readers through a methodical development of the diverse physical processes that shape weather, global energetics, and climate. End-of-chapter problems of varying difficulty develop student knowledge and its quantitative application, supported by answers and detailed solutions online for instructors.

MURRY SALBY is Chair of Climate Science at Macquarie University, Sydney, Australia. He was previously a Professor at the University of Colorado, where he served as Director of the Center for Atmospheric Theory and Analysis. Previously, he was a researcher at the U.S. National Center for Atmospheric Research and at Princeton University. Professor Salby has authored more than 100 scientific articles in major international journals, as well as the textbook *Fundamentals of Atmospheric Physics* (1996). His research focuses on changes of the atmospheric circulation in relation to global structure, energetics, and climate. Involving large-scale computer simulation and satellite data, Salby's research has provided insight into a wide range of phenomena in the Earth-atmosphere system.

Praise for *Physics of the Atmosphere and Climate*

"Salby's book is a graduate textbook on Earth's atmosphere and climate that is well balanced between the physics of the constituent materials and fluid dynamics. I recommend it as a foundation for anyone who wants to do research on the important open questions about aerosols, radiation, biogeochemisty, and ocean-atmosphere coupling."

–Professor Jim McWilliams, University of California, Los Angeles

"Salby's book provides an exhaustive survey of the atmospheric and climate sciences. The topics are well motivated with thorough discussion and are supported with excellent figures. The book is an essential reference for researchers and graduate and advanced undergraduate students who wish to have a rigorous source for a wide range of fundamental atmospheric science topics. Each chapter ends with an excellent selection of additional references and a challenging set of problems. Atmospheric and climate scientists will find this book to be an essential one for their libraries."

–Associate Professor Hampton N. Shirer, Pennsylvania State University

"Murry Salby presents an informative and insightful tour through the contemporary issues in the atmospheric sciences as they relate to climate. *Physics of the Atmosphere and Climate* is a valuable resource for educators and researchers alike, serving both as a textbook for the graduate or advanced undergraduate student with a physics or mathematics background and as an excellent reference and refresher for practitioners. It is a welcome addition to the field."

–Professor Darin W. Toohey, University of Colorado at Boulder

Salby's earlier book is a classic. As a textbook it is unequaled in breadth, depth, and lucidity. It is the single volume that I recommend to all of my students in atmospheric science. This new version improves over the previous version, if that is possible, in three aspects: beautiful illustrations of global processes (e.g. hydrological cycle) from newly available satellite data, new topics of current interest (e.g. interannual changes in the stratosphere and the oceans), and a new chapter on the influence of the ocean on the atmosphere. These changes make the book more useful as a starting point for studying climate change."

–Professor Yuk Yung, California Institute of Technology

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CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Tokyo, Mexico City

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

www.cambridge.org
Information on this title: www.cambridge.org/9780521767187

First published 2012

Printed in the United States of America

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

Library of Congress Cataloging in Publication data
Salby, Murry L.
Physics of the atmosphere and climate / Murry L. Salby. – 2nd ed.
p. cm.
Revised ed. of: Fundamentals of atmospheric physics. 1996.
Includes bibliographical references and index.
ISBN 978-0-521-76718-7 (hardback)
1. Atmospheric physics. I. Salby, Murry L. Fundamentals of atmospheric physics. II. Title.
QC861.3.S257 2011
551.5–dc23 2011033950

ISBN 978-0-521-76718-7 Hardback

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Preface

Global measurements from space, coupled with large-scale computer models, have widened the perspective of atmospheric science along with its subdiscipline, the study of climate. Supporting those tools are proxy records of previous climate upon which rest interpretations of the current state of the Earth-atmosphere system. While opening new avenues of investigation, these modern tools have introduced increasingly complex questions. Many concern the tools themselves. Uncertainties surround the interpretation of observations, especially proxy records of previous climate, how key physical processes are represented in Global Climate Models (GCMs), and discrepancies between those models. These uncertainties make an understanding of the controlling physical processes and limitations that surround their description essential for drawing reliable insight into the Earth-atmosphere system.

Emerging simultaneously with technological advances has been growing concern over the role of humans in global climate. Buttressed by wide-ranging claims of environmental consequences, such concern has been pushed into the limelight of major national and international policy. The popular ascent of climate research has not been without criticism. Notable are concerns over rigor and critical analysis, whereby (i) proxies of previous climate, relied upon in interpretations of current climate, are often remote and ambiguous and (ii) insight into underlying physical mechanisms has been supplanted by models which, although increasingly complex, remain, in many respects, primitive and poorly understood. Despite technological advances in observing the Earth-atmosphere system and in computing power, strides in predicting its evolution reliably – on climatic time scales and with regional detail – have been limited. The pace of progress reflects the interdisciplinary demands of the subject. Reliable simulation, adequate to reproduce the observed record of climate variation, requires a grasp of mechanisms from different disciplines and of how those mechanisms are interwoven in the Earth-atmosphere system.

Historically, students of the atmosphere and climate have had proficiency in one of the physical disciplines that underpin the subject, but not in the others. Under the fashionable umbrella of climate science, many today do not have proficiency in even one. What is today labeled climate science includes everything from archeology of the Earth to superficial statistics and a spate of social issues. Yet, many who embrace the label have little more than a veneer of insight into the physical processes that actually control the Earth-atmosphere system, let alone what is necessary to simulate its evolution reliably. Without such insight and its application to resolve major uncertainties, genuine progress is unlikely.

The atmosphere is the heart of the climate system, driven through interaction with the sun, continents, and ocean. It is the one component that is comprehensively observed. For this reason, the atmosphere is the central feature against which climate simulations must ultimately be validated.

This book builds on a forerunner, *Fundamentals of Atmospheric Physics*. It has been expanded to include climate, while streamlining the presentation for undergraduates in science, mathematics, and engineering. Advanced material, suitable as a resource for graduate students and researchers, has been retained (distinguished by shading). The treatment focuses upon physical concepts, which are developed from first principles. It integrates five major themes:

1. Atmospheric Thermodynamics;
2. Hydrostatic Equilibrium and Stability;
3. Radiation, Cloud, and Aerosol;
4. Atmospheric Dynamics and the General Circulation;
5. Interaction with the Ocean and Stratosphere.

Cornerstones of modern research, these themes are developed in a balance of theory and applications. Each is illustrated with manifestations on an individual day, the same day used to illustrate other themes. In this fashion, the Earth-atmosphere system is dissected in contemporaneous properties, revealing interactions among them. Supporting the development are detailed solutions to selected problems.

Chapter 1 presents an overview of the Earth-atmosphere system, describing its composition, structure, and energetics. It culminates in a discussion of global mean temperature, its relationship to atmospheric composition, and issues surrounding uncertainties in instrumental and proxy records of climate. Chapters 2–5 are devoted to atmospheric thermodynamics. Developed from a Lagrangian perspective, the discussion concentrates on heterogeneous systems that figure in considerations of cloud and its interaction with radiation, as well as the role of water vapor in the global energy budget. Hydrostatic equilibrium and stability are treated in Chapters 6 and 7, which develop their roles in convection and its influence on thermal and humidity structure. Chapters 8 and 9 focus on atmospheric radiation, cloud, and aerosol. After developing the laws governing radiative transfer, the presentation moves to the energetics of radiative and radiative-convective equilibrium. It then considers climate feedback mechanisms, which are discussed in relation to major contributors to the greenhouse effect, and their simulation in GCMs. Chapters 10–16 are devoted to atmospheric dynamics and the general circulation. The perspective is then transformed, via Reynolds' transport theorem, to the Eulerian description of behavior. Large-scale motion is first treated in terms of geostrophic and hydrostatic equilibrium and then extended to vorticity dynamics and quasi-geostrophic motion. The general circulation is motivated by a zonally symmetric model of heat transfer, setting the stage for baroclinic instability. Supporting it is a treatment of thermal properties of the Earth's surface, persistent

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features of the circulation, and interannual fluctuations that comprise climate variablity. The presentation then turns in Chapter 17 to the ocean, its structure, dynamics, and how it influences the atmosphere. The book closes with a treatment of the stratosphere, issues surrounding ozone, and interactions with the troposphere.

This book has benefited from interaction with numerous colleagues and students. In addition to those received earlier, contributions and feedback were generously provided by W. Bourke, J. Frederiksen, R. Madden, E. Titova, D. Toohey, and J. Wu. Figures were skillfully prepared by J. Davis and D. Oliver. Lastly, I am grateful for the understanding and encouragement of my son, without which this book would not have been completed.

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Prelude

The most fruitful areas for growth of the sciences are those between established fields. Science has been increasingly the task of specialists, in fields which show a tendency to grow progressively narrower. Important work is delayed by the unavailability in one field of results that may have already become classical in the next field. It is these boundary regions of science that offer the richest opportunities to the qualified investigator.

Norbert Wiener