THE THEORY OF LARGE-SCALE OCEAN CIRCULATION

Mounting evidence that human activities are substantially modifying the Earth's climate brings a new imperative to the study of ocean circulation. This textbook provides a concise but comprehensive introduction to the theory of large-scale ocean circulation as it is currently understood and established. Students and instructors will benefit from the carefully chosen chapter-by-chapter exercises at the end of the book. This advanced textbook is invaluable for graduate students and researchers in the fields of oceanic, atmospheric, and climate sciences and other geophysical scientists as well as physicists and mathematicians with a quantitative interest in the planetary fluid environment.

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The water sparkles
secret messages of light
I want to learn the code
—N. Samelson, *Home to the Mockingbird* (1971)

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Preface

The purpose of this text is to give a concise but comprehensive introduction to the basic elements of the theory of large-scale ocean circulation as it is currently understood and established. The intended audience is graduate students and researchers in the fields of oceanic, atmospheric, and climate sciences and other geophysical scientists, physicists, and mathematicians with a quantitative interest in the planetary fluid environment.

When I first began to study the physics of ocean circulation, it was the intrinsic scientific interest of the subject that was most apparent and appealing to me. Since that time, evidence has grown strong that human activities are substantially modifying the Earth's climate, with long-term effects that threaten to significantly disrupt the environmental structures on which human life and civilization depend. This troubling development brings a new imperative to the study of the ocean's large-scale circulation as this circulation and its interactions with the atmosphere and cryosphere play a clearly important, but still poorly understood, role in the global climate system. Although the ocean components of most numerical climate models are based on the primitive equations, the dynamics that they represent are essentially those of the planetary geostrophic equations described here, because of the necessarily coarse horizontal resolution of climate-model computational grids. Thus, the present material should be of particular interest to climate dynamicists.

The text is based on lecture notes that accumulated over roughly the last decade, during which I regularly taught a core graduate physical oceanography course on the theory of large-scale ocean circulation. I am grateful to the students in the past few years of these courses who have responded favorably to earlier drafts of these notes and encouraged me to complete them into a text. That these notes did accumulate is, to me, the main argument for finishing them into a text: their existence proves that though much excellent material is available elsewhere, the precise trajectory through the material that has appealed to me differs measurably from other treatments.

Accordingly, it should also be clear that what the text presents as established understanding is, of course, a personal view.

My hope has been to keep the presentation as straightforward as possible. Accordingly, the plan of the book is essentially linear: it is meant to be worked through from start to finish, with not too much in the way of optional topics or branching logic. Some material beyond what I have normally covered in lectures has been added, so it may not be possible to get through the complete text in a single course, especially if alternative topics or perspectives are also to be included. The first six chapters cover topics and models that may be considered classical and generally, if not universally, accepted. Chapters 7 and 8 steer a course toward less charted waters, presenting perspectives that are less well established and based on more recent research in large-scale physical oceanography. Chapter 9 touches on the thermohaline problem, which is otherwise largely neglected in favor of a development using a single density variable, and Chapter 10 contains some brief closing remarks. The emphasis throughout is on the derivation and exploration of the basic elements of the theory rather than on comparison with oceanographic measurements. The equations are, for the most part, left in dimensional form; the figures, however, are mostly in dimensionless form. The reader is encouraged to work through the associated transformations between dimensional and dimensionless variables. Several exercises are provided for each chapter; these range from the straightforward computation and plotting of numerical results for solutions derived explicitly in the text to the use of independent analytical reasoning to obtain extended, related results.

The majority of the material presented in this text is the accumulated result of the efforts of many individual scientists over many decades and longer and is not the result of my own research. As is customary for introductory pedagogical texts, citations of original publications have generally not been added so as to not clutter the narrative line. A few are included in the notes sections that close each chapter to give the reader some entry points into the research literature. Closely related general references, portions of which have substantial overlap with segments of this text, include the excellent texts by Huang (2009), Pedlosky (1987, 1996), Salmon (1998), and Vallis (2006). Some of the exercises are motivated by specific publications such as Huang and Pedlosky (1999), Ledwell et al. (1998), Rhines and Young (1982b), and Webb (1993). I would also like to acknowledge here the general and multi-layered debt of gratitude that I owe to so many members of the extraordinarily generous and dedicated ocean research community, to which I have had the privilege to belong for longer now than I care to admit in print.

Some portions of the text, especially in Section 5.6 and Chapters 7 and 8, closely follow material originally published by the author (or the author and a coauthor, for Section 9.5) in the American Meteorological Society (AMS) *Journal of Physical Oceanography*, on which the AMS holds the copyright. The associated figures are reprinted by permission of the AMS, as indicated in the corresponding captions;

similarly, the redrawn Figure 5.8 is used with permission of the *Journal of Marine Research*. Ocean observations used in the figures were obtained from the *World Ocean Atlas 2005*, which is publicly available from the National Oceanographic Data Center of the U.S. National Oceanographic and Atmospheric Administration, and were processed using routines from MATLAB Oceans Toolbox, which is publicly available from the Woods Hole branch of the U.S. Geological Survey.

I am grateful to Matt Lloyd of Cambridge University Press for his support, encouragement, and patience throughout the project. Many authors have found that book manuscripts eventually can take on a life of their own; when I found that this one had stowed itself away in my backpack for a late fall hike up the Whitewater Trail to Jefferson Park in the Oregon Cascades, I knew it was time to turn it loose, with the hope that a few readers will find in it an approximate match to their own tastes. If the result is ultimately to improve our general community understanding of the physics of large-scale ocean circulation, then the effort will, at least in my own mind, have justified itself.

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