

The sea obscured by vapour that ... slid in one mighty mass along the sea shore ... The distant country, overhung by straggling clouds that sailed over it, appeared like the darker clouds, seen at a great distance apparently motionless, while the nearer ones pass quickly over them, driven by the lower winds. I never saw such a union of earth, sky and sea. The clouds beneath our feet spread to the water, and the clouds of the sky almost joined them.

Dorothy Wordsworth, *Alfoxden Journal*, 1798.

Preface

THIS IS A BOOK ON THE DYNAMICS OF THE ATMOSPHERE AND OCEAN, with an emphasis on the fundamentals and on the large-scale circulation. By 'large-scale' I mean scales between that of the weather (a few hundred kilometres in the atmosphere and a few tens of kilometres in the ocean, which indeed has its own weather) and the global scale. My focus is our own planet Earth, for that is where we live, but the principles and methodology used should be appropriate for the study of the atmospheres and oceans of other planets. And even if we stay at home, I try to take the reader on a journey — from the most basic and classical material to the frontiers of knowledge.

The book is written at a level appropriate for advanced undergraduate or graduate courses; it is also meant to be a useful reference for researchers, and some aspects of the book have the nature of a research monograph. Prior knowledge of fluid dynamics is helpful but is not a requirement, for the fluid equations are introduced in the first chapter. Similarly, some knowledge of thermodynamics will ease the reader's path, but is not essential. On the other hand, the reader is assumed to have a working knowledge of vector calculus and to know what a partial differential equation is.

Atmospheric and oceanic fluid dynamics (AOFD) is both pure and applied. It is a pure because it involves some of the most fundamental and unsolved problems in fluid dynamics — problems in turbulence and wave-mean flow interaction, in chaos and predictability, and in the general circulation itself. It is applied because the climate and weather so profoundly affect the human condition, and the practice of weather forecasting is a notable example of a successful (yes it is) applied science. The field is also broad, encompassing such subjects as the general circulation, instabilities, gyres, boundary layers, waves, convection and turbulence. My goal in this book is to present a coherent selection of these topics so that the reader will gain a solid grounding in the fundamentals, motivated by and with an appreciation for the problems of the real world. The book is primarily a theoretical one, but in a number of places observations are used to illustrate the dynamics and define the problems. And I have tried to lead the reader to the edge of active areas of research — for a book that limits itself to what is absolutely settled would, I think, be rather dry, a quality best reserved for martinis and humour.

This book is a major revision of one that first appeared in 2006, and about half of the material here is new or rewritten. Some of the changes were motivated by the fact that half of the planet lies equatorward of 30°, that about 20% of the mass of the atmosphere lies above 10 km, and that it rains. Overall, I have tried to encompass the most important aspects of the dynamics and circulation of both atmosphere and ocean, for the similarities and differences between the two are so instructive that even if one's interest is solely in one there is much to be learned by studying the other. Where the subject matter verges on areas of research, I have focused on ideas and topics that, I think, will be of lasting value rather than of current fashion; however, this choice is undoubtedly influenced by my own interests and expertise, not to mention my prejudices.

How to Use this Book

This book is a long one, but it might help to think of it as four short ones with a common theme. These books are on the fundamentals of geophysical fluid dynamics (GFD); waves, instabilities and turbulence; atmospheric circulation; and ocean circulation. Each short book forms a Part in this book, and each might form the basis for a course of about a term or a semester, although there is more material in each than can comfortably be covered unless the course hums along at a torrid pace. The ordering of the topics follows a logical sequence, but is not the order that the book need be read. For example, Chapter 1 covers the basic equations of motion for a fluid, including the requisite thermodynamics. The thermodynamics of seawater belongs to and is included in that chapter, but this material is quite advanced and is not needed to understand many of the later chapters, and may be skipped on a first reading. Typically, sections that are more advanced or that are peripheral to the main narrative are marked with a black diamond, \blacklozenge , and sections that contain matters that are not settled or that describe active areas of research are marked with a dagger, \dagger , but there is some overlap and arbitrariness in the markings. In some of these areas the book may be thought of as an entrance to the original literature and it gives my own view on the subject.

Putting the various topics together in one book will, I hope, emphasize their coherence as part of a single field. Still, there are many paths through the woods and the following notes may help steer the reader, although I do not wish to be prescriptive and experienced instructors will chart their own course. In a nutshell, the material of Part I forms the basis of all that follows, and subsequent Parts may then be read in any order if the reader is willing to cross refer, often to Part II. With care, one may also construct a single course that combines aspects of Parts II, III and/or IV.

A basic GFD course

A first course in GFD might cover much of Part I and, in many cases, Rossby waves and possibly baroclinic instability from Part II. If the students have already had a course in fluid dynamics then much of Chapter 1 can be skipped. Some of the thermodynamics may in any case be omitted on a first reading, and a basic course might encompass the following:

For students with no fluid mechanics:

- Equations of motion, Sections 1.1–1.6, omitting starred sections.
- Compressibility, Sections 1.8 and 1.9.
- Energetics, Section 1.10 (optional).

Then, for all students:

- Rotational effects and Boussinesq equations, Sections 2.1–2.4.
- Pressure coordinates, Section 2.6 (optional, mainly for meteorologists).
- Hydrostatic and geostrophic balance, Sections 2.7 and 2.8.
- Static instability, Section 2.10.
- Shallow water equations and geostrophic adjustment: Sections 3.1, 3.2, 3.5, 3.7–3.9.
- Vorticity, Sections 4.1–4.4 (for students with no fluids background).
- Potential vorticity, some or all of Sections 4.5 and 4.6.
- Geostrophic theory, Sections 5.1–5.5.
- Ekman layers, Section 5.7.
- Rossby waves, Sections 6.4 and 6.5, and possibly Section 16.5 on vertical propagation.
- Jet formation, Section 15.1.
- Baroclinic instability, Sections 9.5 and/or 9.6.

One option is to use only the Boussinesq equations (and later the shallow water equations) and the beta plane, eschewing pressure co-ordinates and sphericity, coming back to them later for atmospheric applications. This option also makes the derivation of quasi-geostrophy a little easier.

But meteorologists may well prefer to introduce these topics from the outset, and use pressure coordinates and not the Boussinesq approximation. Many first courses will end after Rossby waves, although a rapidly-moving course for well-prepared students might cover some aspects of baroclinic instability. If waves are being covered separately, then an alternative is to cover some aspect of the general circulation of the atmosphere or ocean, for example the Stommel model of ocean gyres in Section 19.1, which is a pedagogical delight.

Subsequent reading

The other three short books, or Parts to this book, are loosely based on more advanced courses that I have taught at various times, and taken together are an attempt to pull together classical ideas and recent developments in the field into a coherent whole. Each Part is more-or-less self-contained, although some aspects of Parts III and IV build on Part II, especially the sections on Rossby waves and baroclinic instability. An understanding of the essentials of geostrophic turbulence and turbulent diffusion will also help. Provided these sections and the material in Part I is mastered the remaining Parts may be read in any order if the reader is willing to flip pages occasionally and consult other sections as needed. I won't suggest any specific syllabus to follow apart from the contents of the book itself, but let me make a few remarks.

Part II: Waves, instabilities and turbulence

Rossby waves, gravity waves and baroclinic instability could form the first half of a second course on GFD, with wave-mean-flow interaction and/or turbulence the second half. Any one of these topics could be a full course, especially if supplemented from other sources. WKB methods are very useful in a variety of practical problems and can readily be taught in an elementary way. If needs be equatorial waves (Chapter 8) could be treated separately, for it is a little mathematical, and perhaps folded into a course covering equatorial circulation more generally. One might also construct a course based around geostrophic turbulence and the mid-latitude circulation of the atmosphere and/or ocean.

Part III: Atmospheric circulation

My focus here is on the large scale, and on the fundamental aspects of the general circulation — how wide is the Hadley Cell? why do the surface winds blow eastward in mid-latitudes? why is there a tropopause and why is it 10 km high and not 5 or 50 km? and so forth. A basic knowledge of GFD, such as is in the sample course above, is a pre-requisite; other sections of Part II may be needed but can be consulted as necessary. Chapters 14 and 15 form a pair and should be read consecutively, and Chapter 16 is in some ways a continuation of Chapter 5 on waves. There are numerous ways to navigate through these chapters — one might omit the stratosphere chapter, or it could form the basis for an entire course if other literature were added. The same applies to Chapter 18 on the tropics, and here especially the material cuts close to the bone of what is known and other researchers might write a very different chapter.

Part IV: Oceanic circulation

Many of the above comments on atmospheric circulation apply here, as my goal is to describe and explain the fundamental dynamical processes determining the large-scale structure and circulation of the ocean — why do gyres have western boundary currents? what determines the structure of the thermocline? why does El Niño occur? As for Part III, a basic knowledge of GFD, such as is in the sample course above, is a pre-requisite. Chapter 19 on wind-driven gyres is the foundation of much that follows, and Chapter 20 flows naturally from it. The chapters on the meridional overturning circulation and El Niño delve into active areas of research, and again others might have written differently. Both here and in my discussion of atmospheric circulation I take the position of a *practical theoretician*; such a person seeks theories or explanations of phenomena, but they should be relevant to the world about us.

Miscellany and Acknowledgements

The book was written in L^AT_EX using Minion fonts for text and Minion Math from Typoma for equations. I fear that the references at the end disproportionately represent articles written in English and by British and North American authors, for that is the community I have mainly socialized with. The references are simply those with which I happen to most familiar — but this is a lazy choice and I apologize for it. Student exercises, various codes, and all of the figures, may be downloaded from the CUP website or my own website, which is best obtained using a search engine.

Many, many, colleagues and students have helped in the writing of this book, both by offering constructive suggestions and by gently and not so gently pointing out errors and misconceptions. Many thanks to all of you! I acknowledge your input in the endnotes after each chapter, although I am afraid that I have omitted many of you. If you have additional input or find mistakes, please email me. I would also like to thank three of my predecessor authors. The pioneering books by Joe Pedlosky and Adrian Gill paved the way and if those books had not existed I would have had neither the knowledge nor the courage to write mine. And the book by Rick Salmon taught me that careful arguments can be couched in plain language, and that an easy-to-read style can at the same time be clear and precise. I have tried to follow that example.

As with the first edition, this book ultimately owes its existence to my own hubris and selfishness: hubris to think that others might wish to read what I have written, and selfishness because the enjoyable task of writing such a book masquerades as work.