FOREWORD

On reading this wonderful text on Geophysical Fluid Dynamics (GFD) by Benoit Cushman-Roisin and Jean-Marie Beckers, Antoine de Saint-Exupéry's memorable quote regarding artful simplification seems very appropriate:

> In anything at all, perfection is finally attained not when there is no longer anything to add, but when there is no longer anything to take away.

Any scientific endeavor, particularly one that addresses a system as important and complex as the fluid earth, demands a hierarchy of approaches. One must strip away extraneous detail to expose what lies beneath, but also study the emergent behavior that results from the interaction of myriad components. Today, sophisticated computer models simulate virtual earths so comprehensively that even the effect of a cloud's shadow cast on the ocean can be represented. Such models are used to synthesize observations, make projections about the vagaries of the weather or the likely future evolution of earth's atmosphere and ocean under anthropogenic forcing.

But, as Jorge Luis Borges' one-paragraph parable on 'Exactitude in Science' warns us, we should be wary of the danger of plunging headlong into complexity:

> In that Empire the art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a city, and the map of the Empire the entirety of a Province...In time it was realized that the vast Map was Useless.

Like the Empire's perfect cartography, our virtual earths, though far from useless!, are often not the most appropriate tools to figure out where we are, or build understanding and intuition about what matters and what does not. In short, complex models are rather poor pedagogical tools, yet that pedagogy is vital if we are to make wise inferences from them.

In their updated GFD text, the art of intelligent simplification and clear exposition is employed by Cushman-Roisin and Beckers. Carefully chosen models are presented and tailored to the phenomenon at hand so that the reader learns by being taken up and down the modeling hierarchy. Moreover, the parallel development of physical and numerical aspects of GFD, both reinforcing and echoing the other, succeeds in breaking down artificial barriers between analytical and numerical approaches.

John Marshall
Massachusetts Institute of Technology

PREFACE

The intent of *Introduction to Geophysical Fluid Dynamics - Physical and Numerical Aspects* is to introduce its readers to the principles governing air and water flows on large terrestrial scales and to the methods by which these flows can be simulated on the computer. First and foremost the book is directed to students and scientists in dynamical meteorology and physical oceanography. In addition, the environmental concerns raised by the possible impact of industrial activities on climate and the accompanying variability of the atmosphere and oceans create a strong desire on the part of atmospheric chemists, biologists, engineers and many others to understand the basic concepts of atmospheric and oceanic dynamics. It is hoped that those will find here a readable reference text that will provide them with the necessary fundamentals.

The present volume is a significantly enlarged and updated revision of *Introduction to Geophysical Fluid Dynamics* published by Prentice-Hall in 1994, but the objective has not changed, namely to provide an introductory textbook and an approachable reference book. Simplicity and clarity have therefore remained the guiding principles in writing the text. Whenever possible, the physical principles are illustrated with the aid of the simplest existing models, and the computer methods are shown in juxtaposition with the equations to which they apply. The terminology and notation have also been selected to alleviate to a maximum the intellectual effort necessary to extract the meaning from the text. For example, the expressions planetary wave and stratification frequency are preferred to Rossby wave and Brunt-Väisälä frequency, respectively.

The book is divided in five parts. Following a presentation of the fundamentals in Part I, the effects of rotation and of stratification are explored separately in Parts II and III. Then, Part IV investigates the combined effects of rotation and stratification, which are at the core of geophysical fluid dynamics. The book closes with Part V, which gathers a group of more applied topics of contemporary interest. Each part is divided into short, relatively well contained chapters to provide flexibility of coverage to the professor and ease of access to the researcher. Physical principles and numerical topics are interspersed in order to show the relation of the latter to the former, but a clear division in sections and subsections makes it possible to separate the two if necessary.

Used as a textbook, the present volume should meet the needs of two courses, which are almost always taught sequentially in oceanography and meteorology curricula, namely Geophysical Fluid Dynamics and Numerical Modeling of Geophysical Flows. The integration of both subjects here under a single cover makes it possible to teach both courses with a unified notation and clearer connection of one part to the other than the traditional use of two textbooks, one for each subject. To facilitate the use as a textbook, a number of exercises are offered at the end of every chapter, some more theoretical to reinforce the understanding of the physical principles and others requiring access to a computer to apply the numerical methods. An accompanying CD-ROM contains an assortment of data sets and MATLAB™ codes that permit instructors to ask students to perform realistic and challenging exercises. At the end of every chapter, the reader will also find short biographies, which together form a history of the intellectual developments of the subject matter and should inspire students to achieve similar levels of distinction.

A general remark about notation is appropriate. Because mathematical physics in general and this discipline in particular involve an array of symbols to represent a multitude of variables and constants, with and without dimensions, some conventions are desirable in order to maximize clarity and minimize ambiguity. To this end, a systematic effort has been made to reserve classes of symbols for certain types of variables: Dimensional variables are denoted by lowercase Roman letters (such as u, v and w for the three velocity components), dimensional constants and parameters use uppercase Roman letters (such as H for domain height and L for length scale), and dimensionless quantities are assigned lowercase Greek letters (such as α for an angle and ϵ for a small dimensionless ratio). In keeping with a well established convention in fluid mechanics, dimensionless numbers credited to particular scientists are denoted by the first two letters of their name (*e.g.*, Ro for the Rossby number and Ek for the Ekman number). Numerical notation is borrowed from Patrick J. Roache, and numerical variables are represented by tildas ($\tilde{}$). Of course, rules breed exceptions (*e.g.*, g for the gravitational acceleration, ω for frequency and ψ for streamfunction).

We the authors wish to acknowledge the assistance from numerous colleagues across the globe, too many to permit an exhaustive list here. There is one person, however, who deserves a very special note of recognition. Prof. Eric Deleersnijder of the Université catholique de Louvain, Belgium, suggested that the numerical aspects be intertwined with the physics of Geophysical Fluid Dynamics. He also provided significant assistance during the writing of these numerical topics. An additional debt of gratitude goes to our students, who provided us not only with a testing ground for the teaching of this material but also with numerous and valuable comments. The following people are acknowledged for their pertinent remarks and suggestions made on earlier versions of the text, all of which have improved the clarity and accuracy of the presentation: Aida Azcarate, Alexander Barth, Emmanuel Boss, Pierre Brasseur, Hans Burchard, Pierre Lermusiaux, Evan Mason, Anders Omstedt, Tamay Özgökmen, Thomas Rossby, Charles Troupin, and Lars Umlauf. We also would like to thank our wives Mary and Françoise for their patience and support.

Benoit Cushman-Roisin
Jean-Marie Beckers
August 2009

PREFACE OF THE FIRST EDITION

The intent of *Introduction to Geophysical Fluid Dynamics* is to introduce readers to this developing field. In the late 1950s, this discipline emerged as a few scientists, building on a miscellaneous heritage of fluid mechanics, meteorology, and oceanography, began to model complex atmospheric and oceanic flows by relatively simple mathematical analysis, thereby unifying atmospheric and oceanic physics. Turning from art to science, the discipline then matured during the 1970s. Appropriately, a first treatise titled *Geophysical Fluid Dynamics* by Joseph Pedlosky (Springer-Verlag) was published in 1979. Since then, several other authoritative textbooks have become available, all aimed at graduate students and researchers dedicated to the physics of the atmosphere and oceans. It is my opinion that the teaching of geophysical fluid dynamics is now making its way into science graduate curricula outside of meteorology and oceanography (*e.g.*, physics and engineering). Simultaneously and in view of today's concerns regarding global change, acid precipitations, sea-level rise, and so forth, there is also a growing desire on the part of biologists, atmospheric chemists and engineers to understand the rudiments of climate and ocean dynamics. In this perspective, I believe that the time has come for an introductory text aimed at upper-level undergraduate students, graduate students, and researchers in environmental fluid dynamics.

In the hope of fulfilling this need, simplicity and clarity have been the guiding principles in preparing this book. Whenever possible, the physical principles are illustrated with the aid of the simplest existing models, and the terminology and notation have been selected to maximize the physical interpretation of the concepts and equations. For example, the expression *planetary wave* is preferred to *Rossby wave,*and subscripts are avoided whenever not strictly indispensable.

The book is divided in five parts. After the fundamentals have been established in Part I, the effects of rotation and stratification are explored separately in the following two parts. Then, Part IV analyzes the combined effects of rotation and stratification, and the book closes with Part V, on miscellaneous topics of contemporary interest. Each part is divided into short, relatively well contained chapters to provide flexibility in the choice of materials to be covered, according to the needs of the curriculum or the reader's interests. Each chapter corresponds to one or two lectures, occasionally three, and the length is deemed suitable for a one-semester course (45 lectures). Although it is also an inevitable reflection of my personal choices, the selection of materials has been guided by the desire to emphasize the physical principles at work behind observed phenomena. Such emphasis is also much in keeping with the traditional teaching of geophysical fluid dynamics. The scientist interested in the description of atmospheric and oceanic phenomena will find available an abundance of introductory texts in meteorology and oceanography.

Unlike existing texts in geophysical fluid dynamics, this book offers a number of exercises at the end of every chapter. There, the reader/teacher will also find short biographies and suggestions for laboratory demonstrations. Finally, the text ends with an appendix on wave kinematics, for it is my experience that not all students are familiar with the concepts of wave number, dispersion relation, and group velocity, whereas these are central to the understanding of geophysical wave phenomena.

A general remark on the notation is appropriate. Because mathematical physics in general and this discipline in particular involve symbols representing variables and constants, with and without dimensions, I believe that clarity is brought to the mathematical description of the subject when certain classes of symbols are reserved for certain types of terms. In that spirit, a systematic effort has been placed to assign the notation according to the following rules: Dimensional variables are denoted by lowercase Roman letters (such as u, v, and w for the velocity components), dimensional constants and parameters use uppercase Roman letters (such as H for the domain depth, L for length scale), and dimensionless quantities are assigned lowercase Greek letters (such as θ for an angle). In keeping with a well-established convention of fluid mechanics, dimensionless numbers credited to particular scientists are denoted by the first two letters of those scientists' names (*e.g.*, Ro for the Rossby number). Of course, conventions breed exceptions (*e.g.*, g for the constant gravitational acceleration, ω for frequency, and ψ for streamfunction).

In closing, I wish to acknowledge inspiration from numerous colleagues from across the globe, too many to permit an exhaustive list here. I am also particularly indebted to my students at Dartmouth College; their thirst for knowledge prompted the present text. Don L. Boyer, Arizona State University, Pijush K. Kundu, Nova University, Peter D. Killworth, Robert Hooke Institute, Fred Lutgens, Central Illinois College, Joseph Pedlosky, Woods Hole Oceanographic Institution, and George Veronis, Yale University, made many detailed and invaluable suggestions, which have improved both the clarity and accuracy of the presentation. Finally, deep gratitude goes to Lori Terino for her expertise and patience in typing the text.

Benoit Cushman-Roisin
1993