Preface

As stated in the title, this is a book for people interested in modeling convection in planets and stars. It begins with the basics of computer modeling and assumes the reader has no previous computer modeling experience but does have at least a basic understanding of classical physics, vector calculus, partial differential equations, and simple computer programming. The book is a compilation of my lecture notes for teaching students at the University of California Santa Cruz how to write their own computer programs to simulate time-dependent thermal convection, internal gravity waves, and magnetoconvection. I have taught Part 1 of this book as a side project in my graduate and undergraduate courses on fluid dynamics and have included Chapter 11 in my courses on magnetohydrodynamics (MHD). In this way students gain experience in and appreciation for the art of computer modeling, while gaining a much better understanding of the fluid dynamics. In addition, I have taught Parts 2 and 3 to all the graduate students I have supervised at UCSC. Being able to write and debug their own convection programs has become a "rite of passage" for my graduate students to work toward a PhD. The focus of Part 1 and most of Parts 2 and 3 is two-dimensional (2D) models because most numerical methods can be implemented in either 2D or 3D, because 2D models are simpler to write, and because 2D models require far fewer computational resources. With this preparation, some of my students have gone on to write their own, more sophisticated, computer programs to produce original research for their PhD theses; others have chosen to study and modify existing computer programs for their thesis research. By teaching this material over the years I have learned the many subtle issues students typically need to have carefully explained, issues too detailed to be mentioned in research papers. I have made an effort to include these explanations throughout the book.

Part 1, *The Fundamentals*, reviews the concepts and equations of thermal convection and then describes, step by step, how to design a computer program that employs basic numerical methods for solving these equations to simulate convection in a 2D cartesian box of fluid heated from below. Internal gravity waves can be simulated by simply reversing the thermal boundary conditions. By prescribing a stable thermal stratification in part of the fluid domain and an unstable stratification in another part one can simulate a combination of gravity waves and convection. Double-diffusive convection is also a combination of gravity waves and convection; it occurs when buoyancy is due to perturbations in both temperature and composition with the secondary constituent of the fluid being much less diffusive than temperature. The numerical method presented in this part to simulate these types of dynamics is spectral in the horizontal direction and finite difference in the vertical direction, which introduces the reader to these two very different methods. The linear stability problem is first addressed, which provides readers a way to check their time-dependent linear program. Then the nonlinear terms are added to produce numerical simulations. I have chosen the Galerkin method to calculate nonlinear terms so readers gain a better understanding of how energy cascades between spatial scales; a more efficient (spectral-transform) method is described in Part 2. Graphical analyses of the simulated data, including making movies, is also discussed in Part 1.

Part 2, *Additional Numerical Methods*, describes alternative numerical methods that improve accuracy and efficiency and provide more realistic geometry. For example, semi-implicit, instead of explicit, time integration schemes are presented; fully finite-difference and fully spectral methods are discussed; the spectral-transform method for calculating nonlinear terms, instead of the Galerkin method, is described; and a local cartesian geometry is converted into global 2D, 2.5D, and 3D spherical-shell geometries. For efficiency, I include magnetic, density stratification, and rotational terms and equations in the discussion of the numerical methods for 2.5D and 3D spherical-shell convection in Section 10.6 before formally introducing these physical effects in Chapters 11–13. The reader could simply choose to ignore these extra terms until they are needed in Part 3 of this book or could read the introductions to Chapters 11–13 before proceeding through Section 10.6.

Part 3, *Additional Physics*, reviews the effects of magnetic fields, density stratification, and rotation. Chapter 11 (Magnetic Field) does not require any of the material in Part 2; therefore readers who are interested in adding magnetic field to the model described in Part 1 can go directly to Chapter 11. The linear analyses and nonlinear simulations with these additional physical effects are described in detail for 2D simulations; they are also described for 2.5D and 3D in Chapter 13, including two standard benchmarks for global 3D convective dynamos. In the final section (13.7) I list several more sophisticated computer modeling features of planetary and stellar convection that are beyond the scope of this book.

This book could be used by anyone with a basic background in physics, mathematics, and computer programming as a self-study guide to learn how to develop computer programs that simulate convection or other fluid dynamics. Parts of this book could also be taught as supplemental material in courses on classical fluid dynamics, magnetohydrodynamics, stellar structure and dynamics, planetary science, geodynamics, physical oceanography, and atmospheric science. Alternatively, the book could be used for a dedicated, one- or two-semester course on computer modeling of convection in any subset of these fields. Part 1 is presented in a very fundamental way with many details carefully explained to help readers who have had no previous experience in computer modeling. Parts 2 and 3 cover more advanced material with the assumption that the reader has mastered the material in Part 1. *Exercises* at the end of each chapter ask the reader, for example, to derive various mathematical results presented in the text. *Computational projects* are also listed that require computer programming to produce, for example, simulations modified relative to those presented in the text.

I have written the computer programs and have run the simulations for all the examples described and displayed in this book. Online copies of computer graphical movies of some of these are available via the book's Web page at *http://press.princeton.edu/titles/10158.html*. However, I have decided not to include copies of most of the computer programs because the point of the book is to inspire and encourage readers to learn how to design and write programs themselves. I feel too many scientists today rely on computer programs written by a small subset of their scientific community, and run these programs as "black boxes" with little understanding of the approximations that have been made to the equations or the details and limitations of the numerical methods employed to solve the equations. I have, however, included via the book's Web page copies of the basic programs described in Part 1 for those who may need help debugging their programs. Copies of the various subroutines printed in the appendixes can also be downloaded via the Web page.

Although I do cite several papers and books that describe computer modeling studies of convection in planets and stars, the list is far from complete. This book is not meant to be a review of such computer modeling studies; many excellent review papers and books have been written on those topics. I have not described parameterized convection such as that employed in Mixing Length theory (within the astrophysics and planetary communities), in hydrostatic circulation models (within the atmospheric and ocean communities), or in Mean Field models (within the geodynamo and solar dynamo communities). This book is also not a description of the latest and most sophisticated numerical or programming methods for modeling convection in planets and stars; more advanced reviews and books very adequately describe such methods. Instead, this book is meant to be a tutorial for those wishing to learn the basics of writing and using computer models of convection. Hopefully, all readers will gain an appreciation and excitement for computer modeling and some will go on to improve existing computer programs or write completely new ones.

I wish to thank the three reviewers for their helpful suggestions. I also want to thank my former and current students who have given me very useful feedback; I originally developed these 2D models as teaching tools for them. It is my hope that several of my students will find this book useful for teaching their students someday.

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