Preface

Many excellent textbooks describe the physics of climate and give an introduction to the processes that interact and feedback to produce the earth's weather and climate [178, 79, 133, 94, 83, 134]. In this book we approach the subject from another direction, admitting from the outset that the definition of climate is nebulous and, in fact, still evolving. The climate will be viewed as multifaceted but always as the solution of a particular mathematical model. That all climate models are incomplete is a consequence of our lack of understanding of the physics as well as the incompleteness of mathematical knowledge.

The understanding of the nature of the earth's climate has improved and changed as the mathematical notions of what constitutes a solution to a set of partial differential equations has changed.[1] The development of theories of deterministic chaos and the existence of global attractors as invariant subsets of the time evolution associated with the Navier–Stokes equations have had a profound influence on climate research [165]. The invariants of flows, what is conserved, and what coherent structures persist inform the theory of climate. How oscillations, bifurcations, and singularities arise in the solutions of partial differential equations is fundamental to drawing a line between natural climate variability and human induced climate change. A SIAM focus for 2013 on the "Mathematics of Planet Earth" was marked with the notable publication of Kaper and Engler's text [100] treating many of the current conceptual models of climate.

The role of general circulation models and high-end computer simulation in the understanding of climate should not be underestimated. Describing the principles and practice of this type of modeling is the primary focus of this book. The first chapter is devoted to the observations of weather phenomena and the special programs to collect climate data that provide a wealth of information for calibration, validation, and verification. The data themselves, however, do not provide the interpretation of climatic events or give a means of projecting future climate responses. Only high-end models show how the processes interact and feedback upon one another culminating in weather phenomena and climate. Chapter 2 introduces the governing equations of geophysical flow that model the circulations of the atmosphere and ocean. Chapter 3 introduces numerical methods for solving these equations starting from a simplified subset known as the shallow water equations. High performance computing is a uniquely powerful tool to probe the solutions of the equations that constitute the model, and this is introduced in Section 3.9. Numerical methods and algorithms are the backbone of simulations based on general circulation models. Attention is given to parallel algorithms and promising numerical methods that will likely figure in the next generation of climate models.

Chapter 4 describes what has been learned from climate simulations, and a few case studies are presented with the hope that interested readers and students will pursue other

[1]The mathematical theory for atmospheric and ocean flows is not complete [26, 164], so there is still room for growth.

simulation studies following their own interests. Finally, a brief chapter introduces some of the methods and mathematical basis for the analysis of climate. These methods must be used to summarize simulation results and, of course, are useful in analyzing weather data to extract climate statistics and trends.

Exercises are scattered throughout the text as well as references to MATLAB codes that are part of these exercises and are described in supplemental material available online at www.siam.org/books/MM19. Since methods and simulation are a thread throughout the material, students wishing to master the material should gain experience with computer simulation and programming through these exercises. Full-fledged simulations using parallel computers requires more sophisticated programming than the MATLAB environment offers. Usually simulation codes are written in FORTRAN and C++. But access to the full code and simulation system of the Community Climate System Model is available to the ambitious reader. For analysis, Python or the NCAR Command Language (NCL) are the languages of choice.

Reference is also made to Supplemental Lectures [49], provided in a separate online volume at www.siam.org/books/MM19. These lectures each start with something we know fairly well, usually some piece of mathematics, but then branch out to things we do not understand well. The supplemental lectures serve as a somewhat light-hearted introduction to research areas where open questions still exist and important perspectives are emerging. Students seem to appreciate the change of pace offered in these lectures.

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