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**Stephen Griffies: Fundamentals of Ocean Climate Models**

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# Chapter One

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## OCEAN CLIMATE MODELS

The purpose of this chapter is to introduce ocean climate models and their use in climate science.

### 1.1 OCEAN MODELS AS TOOLS FOR OCEAN SCIENCE

A column of ocean water only 3m thick contains as much heat capacity as the full atmospheric column above (Gill, 1982). Hence, the oceans, which cover roughly 70% of the earth's surface, provide a large reservoir for heat and other constituents of the earth's climate system, such as the increasing amounts of anthropogenic carbon dioxide. Through its buffering abilities and relatively slow time scales, the ocean represents the flywheel of the earth's climate system. That is, as goes the ocean, so goes the climate system.

A scientific understanding of the ocean's time mean state, as well as its variability about this mean and its stability to various forms of perturbations, represents a key goal of physical oceanography and climate science. Due to our inability to perform controlled experiments on large-scale systems studied in the geosciences, such as the earth's climate and its component subsystems, computer models represent a critical tool for rationalizing climate phenomena. Indeed, computer models are becoming the primary tools used to study and predict physical, chemical, and biological characteristics of the ocean fluid, reflecting the growing power of computers, improved knowledge and observations of the ocean, and enhancements in the realism of ocean model simulations.

That ocean models are increasingly being used by all sorts of scientists, including those without direct experience developing models, is a sign that the models have enhanced their physical integrity over the past decades to a level deserving a general respect within the broader climate science community. Correspondingly, as model usage increases, model developers have a growing responsibility to ensure that their codes are physically based, numerically sound, and well documented. Given this mandate, one aim of this book is to establish a level of ocean model documentation that goes beyond the usual technical discussion that assumes the model user is familiar with the fundamentals and understands the physical meanings of the mathematical symbols. Instead, we develop the equations from a (mostly) first principles perspective and take some care to nurture a physical understanding of the mathematics.

## 1.2 OCEAN CLIMATE MODELS

Models of the ocean range in complexity from idealized theoretical models whose solutions can be summarized by a few lines of mathematics, to realistic global ocean circulation models encompassing many equations and requiring thousands or millions of lines of computer code to solve. The main focus of this monograph concerns the realistic models, and in particular the fundamentals of their formulation. It is important to note that a scientific understanding of ocean climate phenomena is often realized most profoundly by the creative and judicious use of a hierarchy of models. The most realistic models play an important part in this hierarchy, but they are not the full story.

We use the term *ocean climate model* as a means to distinguish models that simulate the World Ocean over climatologically relevant time scales from those that simulate, say, coastal, regional, or basin scale dynamics. Distinctions between these ocean modeling subfields is decreasing, largely due to the steady growth in computer power that allows modelers to dispense with some of the simplifications required only a few years ago. Distinctions are also becoming fewer due to realizations by practitioners that elements of the ocean strongly interact across many spatial and temporal scales. That is, ocean modeling subfields overlap in crucial manners. Nonetheless, the finite nature of both scientists and their tools introduces a difference in focus, with choices made by practitioners in one subfield often unacceptable to those in another.

Simulations of the World Ocean over time scales appropriate for climate (e.g., decades to millennia) involve extremely rich and complex arrays of flow regimes and interactions between components of the climate system. Additionally, the ocean is largely forced at its upper and lower boundaries, with interior flow relatively ideal. In particular, high latitude oceanography involves strong interactions between the ocean with sea ice and rivers, and intense air-sea heat fluxes induce deep convection and the associated formation of deep water masses. Tropical oceanography involves intense equatorial current systems with rapid adjustments to wind forcing associated with equatorial Kelvin, Rossby, and instability waves, and a powerful interannual mode of air-sea variability known as El Niño in the Pacific. Oceanography in the subtropical and subpolar latitudes is dominated by large-scale gyres with meandering and eddying boundary currents forming their western margins. Furthermore, solid earth boundaries provide a leading order influence on the ocean circulation. For example, meridional boundaries block otherwise zonal flow except within certain parts of the Southern Ocean, variations in topography cause flows to feel the bottom throughout many crucial parts of the World Ocean, and straits and sills funnel water from marginal seas, such as the Mediterranean and Greenland, into the larger ocean basins. A primary goal of ocean climate modeling is to simulate the global ocean circulation over these various regimes, given just the boundary forcing. This is a highly nontrivial goal.

As discussed in Section 6.2, there are three general model classes that have been used for ocean modeling. These classes are distinguished by the manner used to discretize the vertical direction. Indeed, as argued in Griffies et al. (2000a), the choice of vertical coordinate represents the most fundamental choice that can be made when designing an ocean model.

Since the 1960's, *z-coordinate* ocean models, or simply *z-models*, have been the

dominant class for global ocean climate simulations. This is the model class with which the author is most familiar, and which forms the focus of some of the latter parts of this book. Characteristics of  $z$ -models, as well as the other two classes (*isopycnal* and *terrain following*), are described in Section 6.2. Each model class has advantages and disadvantages when simulating various flow regimes encountered in ocean climate modeling. Only two of the three (*isopycnal* and  $z$ ) have routinely been used for global circulation studies. One reason that  $z$ -models presently dominate ocean climate modeling is that their relative simplicity has allowed them to be used for many decades, going back to the work of Bryan (1969), Bryan and Lewis (1979), and Cox (1984). In contrast, the *isopycnal* model class requires more sophisticated numerical schemes, whose development did not mature until the 1980's. The third model class, the *terrain following sigma* models, remain the model of choice for coastal oceanographers, but they have largely remained absent from simulations of global ocean climate.

Ocean climate models continue to evolve. For example, many egregious problems identified with early representatives of the different model classes are now remedied by more mature numerical treatments. Nonetheless, as argued in Section 6.2, each class has basic limitations that warrant developing models with generalized vertical coordinates. The hope is that by generalizing the treatment of the vertical, a well-designed model with this capability can reduce or remove many of the egregious problems of the less flexible models based on a single vertical coordinate choice. This remains a topic of intense research in the ocean model development community.

Research into ocean model fundamentals and algorithm development can take many years to penetrate into the common practice of major climate modeling centers. The reason is largely related to the extreme complexity involved with building coupled global climate models. It takes teams of researchers years to build and refine a coupled model, with significant feedback and compromise necessary in order to successfully mesh the needs of various component modelers. Notably, an ocean model suitable for coupled climate simulations is far more than a dynamical kernel. In addition, it must consist of a full suite of physical parameterizations of unresolved processes, diagnostics allowing its simulations to be readily analyzed, infrastructure providing a means to *talk* to the computer that is running the model, a superstructure with appropriate handles for interacting with other component models (e.g., sea ice and atmosphere models) necessary for climate simulations, and computational sophistication rendering it efficient on the many computer platforms employed by research laboratories and universities.

### 1.3 CHALLENGES OF CLIMATE CHANGE

Since the 1990's, thousands of scientists worldwide have been contributing to the development of extensive reports on climate change science, with the latest being Houghton et al. (2001). This work is in response to the increasing scientific evidence that industrial society represents a nontrivial geophysical force. Common questions that arise are: What should we expect? How much of the observed climate change is due to humans? Providing sound scientifically based answers to these and other questions is profoundly difficult. Indeed, as lucidly described in

the book by Philander (1998), unequivocal answers are not forthcoming from climate science. Instead, as with weather prediction, probabilistic statements are the best the science can provide.

As discussed in Houghton et al. (2001), we are at a stage in climate science where the wide variety of climate models yield a general consensus regarding the large-scale effects of increased greenhouse gases. Quite simply, the planet is warming and will likely continue to do so, with higher latitudes feeling the relative effects more than lower latitudes. However, when quantitative questions are posed, models provide varying projections. Part of the spread is related to the chaotic nature of the climate system. Part is due to large uncertainties in future greenhouse gas emission scenarios. Yet some is due to differing details of the model formulations and their parameterizations. It is on this latter issue that climate scientists can make further progress through research and development.

Given the critical importance of models for understanding climate and predicting its future behavior, it is incumbent on model developers to impose the highest standards on model integrity. In particular, ocean climate models should incorporate realistic parameterizations and sound numerical formulations (for reviews, see Chassignet and Verron, 1998; Griffies et al., 2000a). Yet they must do so at a level of computational expense that does not overly handicap the abilities of the earth system modeler to incorporate other components of the climate system, and to fully investigate various scenarios. Within the ocean science community, this mandate to improve the models entrains hundreds of researchers such as process oriented physicists, chemists, biologists, observational oceanographers, numerical algorithm developers, software engineers, ocean climate modelers, and others. It is anticipated that the questions of climate change will continue to strongly influence and motivate all areas of climate science for many years.