Xie, S.-P., 2023: *Coupled Atmosphere-Ocean Dynamics: From El Nino to Climate Change*. Elsevier Science.

Preface

Climate affects natural environment and human society. Climate variability drives, and climate change exacerbates, extreme events such as heatwaves, droughts, and flooding. As society becomes increasingly sophisticated and sensitive to climate variations, evaluating and understanding climate influence in a wide range of data is important and essential.

This book presents core coupled ocean-atmosphere dynamics that gives rise to recurrent spatial patterns, preferred timescales and predictability of our changing climate. It is based on a course I have taught over 25 years, mostly at graduate level but twice at upper-division undergraduate level. I have lectured the course, in part or full, at summer/winter schools and training workshops around the world.

i. Ocean-atmosphere coupling

El Nino refers to the anomalous warming of the equatorial Pacific Ocean. From the oceanographic point of view, the Pacific warms because the atmospheric Southern Oscillation relaxes the prevailing easterly winds on the equator. From the meteorological point of view, on the other hand, the easterly winds weaken because of the equatorial Pacific warming (El Nino). This circular argument implies that El Nino is not merely an oceanic phenomenon, nor the Southern Oscillation an atmospheric one; they are the two sides of the same phenomenon arising from their mutual interaction. This revolutionary idea led to the coinage of the term El Nino and the Southern Oscillation (ENSO) to emphasize the coupled nature of the phenomenon. Thus a new field of study, coupled atmosphere-ocean dynamics, was born.

ENSO research led to the integration of meteorology—the atmospheric science of weather—and physical oceanography. Meteorology and physical oceanography share a common set of concepts and principals of geophysical fluid dynamics (GFD), for which the effect of Earth rotation known as the Coriolis force is important. The dynamical approach led to numerical weather prediction and explained why major currents are found near the western boundaries of ocean basins. Excellent texts treating atmospheric and ocean dynamics from the unified view of GFD include Pedlosky (1982), Gill (1982), and Vallis (2017).

Coupled ocean-atmosphere dynamics culminated into the successful prediction of El Nino by Cane et al. (1986). I entered the graduate school that year and spent the first year reading Gill's (1982) classic text, where "fundamental physical ideas and dynamical theory are skillfully interwoven with observed phenomena" (Batchelor and Hide 1988). Gill's (1982) text was published just before the dawn of coupled dynamics. The phrase ENSO had yet been coined but the field was at the threshold of a scientific revolution that views ENSO as a spontaneous, coupled ocean-atmosphere oscillation.

ii. Aims of the book

This book starts where Gill's (1982) text left off, with the title emphasizing our focus on exciting advances in the *coupled* approach to climate variability and change. There are excellent monographs on ENSO (Philander 1990; Clarke 2008; Sarachik and Cane 2010; McPhaden et al. 2020), but the field has expanded to encompass climate variability in other ocean basins and anthropogenic climate change. This book aims to synthesize coupled dynamics of both natural variability and anthropogenic change, in and out of the tropics, including but beyond ENSO. It builds the physical foundation for broad climate impact studies.

For students and researchers of ocean, atmospheric and climate sciences, the book retains the rigor by including key equations with references to classic texts (Gill 1982; Holton 2004) or the original literature where the full mathematical treatment can be found. Equations are introduced and explained in plain, descriptive language so readers with limited prior exposure to fluid mechanics can follow the discussion of essential physical processes and mechanisms at work. The large number of illustrations and the narratives further aid the conceptual understanding.

iii. Organization

The book consists of three parts that are closely inter-related. Part I (chapters 2-6) examines tropical and subtropical climates mostly from an atmospheric perspective. Chapter 2 starts from the planetary energy balance, illustrates the characteristics and mechanisms of ocean-atmospheric energy transports, and highlights the role of the meridional overturning circulation. Chapter 3 examines atmospheric deep convection, the heat source that drives the global atmospheric circulation. Equatorial waves are introduced and their role in atmospheric adjustments to convective heating is illustrated. Chapter 4 studies the 30-60 days Madden-Julian Oscillation (MJO), a planetary-scale mode spontaneously arising from interactions of atmospheric deep convection and circulation. Chapter 5 introduces monsoons, a product of land-atmosphere-ocean interactions that affects more than half of the world population. We discuss atmospheric dynamics that makes each regional monsoon unique and at the same time, connects them across the great span from Africa to Asia. Chapter 6 shifts the focus onto subtropical regions of subsidence, where a temperature inversion caps the atmospheric boundary layer. Low-level clouds and the underlying ocean interact, giving rise to positive feedback important for a range of phenomena.

Part II (chapters 7-11) is the core of the book and investigates ocean-atmosphere interactions in tropical climatology and interannual variability. Chapter 7 introduces a reduced-gravity model of the upper ocean and discusses the ocean adjustments to changing winds. Chapter 8 revisits the tropical rainfall distribution first outlined in Chapter 3, but from the perspective of coupled ocean-atmosphere interaction. Questions to be addressed include: why is the tropical rain band—known as the intertropical convergence zone (ITCZ)—displaced north of the equator, and what causes the marked annual oscillation in temperature and rainfall on the equator over the eastern Pacific and Atlantic? Chapter 9 opens with a description of ENSO as a coupled ocean-atmospheric phenomenon and then illustrates the positive Bjerknes feedback that arises from the coupling. It further discusses how slow ocean adjustment processes, not in equilibrium with the wind variations, cause the tropical Pacific to oscillate between El Nino and La Nina. The last point enables prediction at seasonal lead times of ENSO and its global effects. Chapters 10 and 11 discuss regional climate and interannual variability over the tropical Atlantic and Indian oceans, respectively. The mean climate is distinct in important ways between these tropical oceans, but they share a common equatorial mode of Bjerknes feedback. A unique coupled mode across the Indo-western Pacific explains a mysterious post-ENSO effect on summer monsoons from India to China.

Chapter 12 shows that climate variability is dynamically distinct in and outside the tropics. In the extratropics, atmospheric internal variability is strong and organized into coherent spatial patterns because of the zonal variations in the mean westerly jet. It drives oceanic variability while ocean feedbacks are nonlocal and weak. While tropical teleconnections to the extratropics are well established, we highlight recent ideas that extratropical variability has important effects the other way around on tropical climate. Anthropogenic emissions of greenhouse gases and aerosols perturb the planetary energy balance, causing Earth's climate to change at unprecedented rates. While global-mean surface temperature increase has traditionally been emphasized, we focus on regional climate change unleashed by global warming. After a brief introduction to climate feedback on global mean surface temperature, Chapter 13 discusses robust changes expected in a warmer climate that do not fundamentally depend on the ocean-atmospheric circulation change (so-called thermodynamic effect). Chapter 14 focuses on regional climate change, including a comparison of forcing by well-mixed greenhouse gases vs. highly distributed aerosols. Spatial patterns of ocean heat uptake and warming are an important factor driving regional variations in tropical rainfall change.

iv. Pedagogical features

This book aims at a comprehensive and systematic treatment of large-scale ocean-atmosphere interactions. This allows a wide range of comparative views: climate modes among and across different tropical ocean basins (chapters 9-11), the effects of the basin size and degree of continental/monsoon influence, zonal vs. meridional mode that peaks/vanishes on the equator, ocean feedback on the atmosphere in vs. out of the tropics (chapter 9 vs. 12), spontaneous internal oscillations vs. externally forced climate change (chapter 13), and greenhouse vs. aerosol forcing (chapter 14). Such comparative views offer unique insights into the mechanisms for climate variability and predictability.

Side boxes are used to introduce related topics and/ provide historical accounts of major breakthroughs in climate dynamics that have changed our view of the climate system. I know many of the pioneers who led the breakthroughs and asked them about what inspired them to probe what seemed unimportant, to connect what had been apart, to predict beyond the chaos of weather. These historical accounts offer real-life examples that knowledge is not static but in constant expansion, driven by curiosity, daring imagination, and innovation.

The book can be used standing alone or in combination with other material for a range of courses. My graduate course at UCSD typically covers the first 12 chapters with some simplifications. Some of the chapters (3, 5, 9, and 12) may require two lectures to cover fully. It is also possible to skip chapters 4-5 and cover chapters 13-14. The 10-week long course consists of 16 80-minute lectures and a 160-minute colloquium in which each student is required to make a presentation on a paper(s) related to a class topic. A list of suggested papers is available as online resources. Climate is local, and regional climate inspire interest in coupled atmosphere-ocean dynamics. Instructors may wish to supplement material to meet interests in local climate. At UCSD, for example, subtropical climate (chapter 6) gets the full coverage while skipping the sections on East Asian and African monsoons (chapter 5) and treating lightly chapters on the tropical Atlantic and Indian oceans. In Asia, on the other hand, my lectures give Asian monsoons and the Indian Ocean the full treatment, while omitting chapters on subtropical climate and the Atlantic Ocean.

Review questions are provided at the end of chapters to reinforce key concepts and applications. Online resources include figures in the book, PowerPoint slides for my UCSD class, homework problems, and errata.

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