Physical Oceanography and Climate

Climate research over recent decades has shown that the interaction between the ocean and atmosphere drives the global climate system. This engaging and accessible textbook focuses on climate dynamics from the perspective of the upper ocean, and specifically on the interaction between the atmosphere and ocean. It describes the fundamental physics and dynamics governing the behavior of the ocean, and how it interacts with the atmosphere, giving rise to natural climate variability and influencing climate change. Including end-of-chapter questions and turn-key access to online, research-quality data sets, it allows readers the chance to apply their knowledge and work with real data. Comprehensive information is also provided on the data sets used to produce the numerous illustrations, allowing students to dive deeper into the data themselves. Providing an accessible treatment of physical oceanography, it is perfect for intermediate to advanced students wishing to gain an interdisciplinary introduction to climate science and oceanography.

Kris Karnauskas is Associate Professor in the Department of Atmospheric and Oceanic Sciences and Fellow of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder, with a secondary faculty appointment in the Colorado School of Public Health. Prior to these positions he was a member of the scientific staff at the Woods Hole Oceanographic Institution. Kris currently serves as Editor of the *Journal of Geophysical Research – Oceans* and recently served on the Scientific Steering Committee of the US Climate Variability and Predictability Program. Kris was the recipient of the 2017 Ocean Sciences Early Career Award from the American Geophysical Union. He is frequently a contractor to the United Nations Development Programme, providing expertise on regional climate change impacts for small island nations.

'From Ekman to ENSO, Prof Karnauskas covers all the essential classic and modern topics of oceanic and atmospheric dynamics, including their interactive physics from the outset, using a lively style of writing enhanced with compelling graphics that will appeal to a wide range of advanced undergraduates in physical oceanography and climate sciences, as well as to cross-disciplinary Earth system scientists in Ph.D. programs. His writing style is refreshingly accessible through his colorfully expressive descriptions, which are firmly rooted in the indispensable mathematical foundations, that render clear expositions of the key topics that link together the intricate dynamics and thermodynamics of climate variability and climate change. He presents a novel and uniquely integrated perspective of climate variability, ocean-atmosphere interactions, and global warming, vividly illustrated with his self-designed schematic diagrams based on his own vast experience in studying both components of the system and their communication through the air-sea interface.'

– Arthur J. Miller, Scripps Institution of Oceanography, University of California, San Diego

'By standing at the ocean's surface and looking at the ocean through a climate lens, this advanced undergraduate text provides a focused view of the essential place of the ocean in the coupled climate system. With vivid prose and clear explications of mathematical necessities Karnauskas has created an exceptionally efficient means to understand the climate system. Its "deep dives into data" is an appealing feature that makes it easy for the student to explore the climate on her own. At this time of urgent interest in climate this book should find the wide audience it deserves.'

– Mark A. Cane, Lamont-Doherty Earth Observatory, Columbia University

'This text book gives an accessible and comprehensive overview of the processes in the ocean that are important for climate, for upper level undergraduates to graduate students in the ocean and atmospheric sciences. Unlike other books that focus on this topic, this book provides questions at the end of each chapter that encourage students to grapple with the material, both conceptually and quantitatively. Even better, there is explicit connection to the peer-reviewed literature that encourages students to see applications of the concepts to the practice of science. The connection of the material to observational data sets through the *Dive into the Data* boxes in each chapter introduces students to data-driven discovery in ocean sciences.'

– LuAnne Thompson, University of Washington

'A new textbook that captures the physics of our coupled atmosphere-ocean system. This is no ordinary textbook. It takes us on a journey in exploring and understanding the physics of our planet's two fluids (one ocean, one atmosphere) and how they talk to each other. Using an easy style of writing without compromising the mathematics, Karnauskas draws us into some of the history of scientific discovery of our ocean and atmosphere, while also presenting the physics and mathematics of fluid dynamics and the interactions between these two fluids. Each chapter poses questions for furthering the reader's discovery and thinking, often through the use of data sets. The book leads us ultimately to a discussion on the atmosphere-ocean system by describing climate not as an average of weather, but as an interacting system that produces climate variability and change. I highly recommend this textbook, written by a new leader in the study of our planet.'

– Susan K. Avery, Woods Hole Oceanographic Institution

' … an important and timely text that focuses squarely on the role of the ocean in the climate system. It is cleverly organized to present the oceanography that will help the reader understand the role of the ocean in climate dynamics. It is written in an accessible form that make it valuable both as a textbook and a reference book.'

– Enrique Curchitser, Rutgers University

'*Physical Oceanography and Climate* fills a gap in the scientific literature at a time when the societal issues surrounding climate variability and change are becoming ever more urgent. This engagingly written book, with its focus on fundamentals and hands-on learning exercises, is a great introduction to the ocean's role in climate and why it matters. It will serve as a valuable resource for students and research scientists interested in the processes that govern ocean-atmosphere interactions and their consequences for the climate system.'

– Michael J. McPhaden, University of Washington

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Dive into the Data

Written by a prolific research scientist, *Physical Oceanography and Climate* makes use of dozens of publicly available, research-quality data sets to render vivid illustrations of the core scientific concepts taught throughout the book. *Dive into the Data* is a book feature that enables students (and instructors) to actually *use* real, research-quality data sets to go beyond the graphs. There is one *Dive into the Data* box for every major data set used – roughly three per chapter, or 27 in total. These boxes are meant to accelerate the process of hands-on learning and exploration regardless of skill level; they can form the basis for a wide range of homework assignments, lab activities, term projects, etc.

Each *Dive into the Data* box includes the full data set name and version, lists which figures in the book utilize the data set, some key metadata such as the spatial and temporal aspects of the data set (domain and resolution), a plain-language synopsis of the data set and its typical scientific uses, the original source (URL) of the data set and what format is found there, and the filenames of the value-added resources provided by the book author (neatly packaged, easy-to-use MATLAB data files and sample codes) available at www.cambridge.org/karnauskas. Finally, the questions at the end of each chapter include a subset of questions that encourage (or require) students to access and analyze the data sets described in *Dive into the Data* boxes. Following is a complete list of *Dive into the Data* boxes by chapter.

Chapter 1

1. Antarctic Composite Ice Core Atmospheric CO_2
2. Atmospheric CO_2 at Mauna Loa Observatory
3. Representative Concentration Pathway (RCP) Global Mixing Ratios of Atmospheric CO_2

Chapter 2

1. WHOI Ocean–Atmosphere Flux (OAFlux)
2. NOAA Optimal Interpolation (OI) Sea Surface Temperature (SST)
3. NOAA Tropical Atmosphere–Ocean (TAO) Array

Chapter 3

1. Aquarius Sea Surface Salinity
2. Roemmich–Gilson Argo Climatology
3. Global Precipitation Climatology Project (GPCP)
4. Simple Ocean Data Assimilation (SODA) Reanalysis
5. IFREMER Mixed Layer Depth (MLD) Climatology

Chapter 4

1. Cross-Calibrated Multi-Platform (CCMP) Ocean Surface Winds
2. Ocean Surface Current Analysis Realtime (OSCAR)
3. AVISO Sea Surface Height

Chapter 5

1. Western Tropical Pacific Merged Ocean–Atmosphere Temperature Profiles
2. CERES Top of Atmosphere (TOA) Energy Budget
3. NOAA Interpolated Outgoing Longwave Radiation (OLR)
4. NOAA/NCEP-DOE Reanalysis 2

Chapter 6

1. MODIS Sea Surface Temperature (SST)
2. MODIS Surface Chlorophyll Concentration

Chapter 7

1. NASA GISS Surface Temperature Analysis (GISTEMP)

Chapter 8

1. World Ocean Circulation Experiment (WOCE) Hydrographic Profiles
2. Global Benthic $\delta^{18}O$ Stack
3. North Greenland Ice Core Project (NGRIP) $\delta^{18}O$ Record
4. RAPID Array
5. NOAA Extended Reconstructed SST (ERSST)

Chapter 9

1. Coupled Model Intercomparison Project, Phase 5 (CMIP5)

Preface

This book was written based on the need for an accessible yet quantitative treatment of physical oceanography for those students whose true motivation is to understand climate variability and change. It was born out of a course by the same name, which I developed and have taught in the Department of Atmospheric and Oceanic Sciences at the University of Colorado Boulder since the fall of 2015. There are quite a few programs like ours nowadays, where oceanography and atmospheric science fall under a single undergraduate curriculum. Moreover, the broad recognition across the Earth sciences of the importance of interdisciplinary competency has brought many graduate students to my classroom from closely related disciplines ranging from paleoclimatology to science journalism. This tells me there is a steadily growing population of students who are studying other realms of the climate system (atmosphere, cryosphere, biosphere, carbon cycle, etc.), not to mention an informed public, who want to know more about how the ocean fits in. That is exactly the role this book aims to fill.

To that end, this is not a traditional "GFD" (geophysical fluid dynamics) book. Some topics that one might expect to see in such a pure physical oceanography text, like surface waves or tides, are omitted here in the interest of keeping the material germane to those motivated primarily by climate. This book provides a course on global climate dynamics from the perspective of the upper ocean – the mixed layer, to be specific. Why do sea surface temperature anomalies develop? How does ocean salinity respond to the atmosphere like a rain gauge? What drives the circulation of the ocean, and where are the parallels with the governing equations of the atmosphere? This book introduces these fundamentals in a unified budget framework that quickly becomes familiar to the student as we apply it to the conservation of energy, mass, and momentum. Those budgets are cast in such a way as to deliberately and readily identify the points of contact between the ocean and atmosphere, leading to the wind-driven and thermohaline circulations, the mechanisms by which the resultant variations in temperature at the ocean surface influence the atmospheric circulation, and how those interactions give rise to *coupled* climate variability from interannual to multidecadal and longer time scales. Finally, the closing chapter offers a grand view of anthropogenic radiative forcing and global climate models before delving into some of the pathways by which climate change rears its head in the ocean.

The book is ideal for a one-semester, upper-level undergraduate course in a department of atmospheric science and/or oceanography, or an elective graduate course in virtually any department within the Earth sciences. At the University of Colorado Boulder it is offered as both at once, and that works great, too. I typically divide the semester into three units with an exam following each. After setting the stage, the first unit introduces conservative budgets in the form of partial differential equations to explore what sets the temperature and salinity of the upper ocean (Chapters 1–3). The second unit delves into dynamics, culminating in an understanding of the wind-driven ocean circulation (Chapters 4–6). The final unit focuses on variability and change in the climate system with an emphasis on ocean-atmosphere coupling (Chapters 7–9). Alternatively, one could split the course into two halves: one covering all of the underlying budgets through momentum (Chapters 1–4), and one rich in applications to steady circulations and climate variability alike (Chapters 5–9).

The writing in this book closely reflects my own teaching style. I'm precise, but not always too formal. The dynamics and mathematical derivations are accompanied by plain-language discussion and schematics. This is a skill possessed by some of my own teachers who I strive to emulate – Jonathan Martin at the University of Wisconsin Madison comes to mind as a master of the craft. I have also made a deliberate attempt in each chapter to highlight the diversity of ocean and climate scientists making exciting progress and discoveries in this field. My years of engagement with US CLIVAR serve as one important source of inspiration in that regard. I am always inspired by my friends, peers, colleagues and mentors, and I think they all deserve to have their work highlighted in textbooks being used to educate the next generation.

I would like to give a special thanks to Matt Lloyd and the entire team at Cambridge University Press for their patience and guidance through the process of developing and writing a book. I thank Elizabeth Maroon, Raghu Murtugudde, Ray Schmitt, and other anonymous reviewers who provided helpful comments on draft chapters. A very hearty thanks also goes out to one of the brightest undergraduates the University of Colorado Boulder has ever seen, Michelle Maclennan, for a thorough and insightful review of the complete work from the most important perspective of all: that of the student. This book and its many illustrations draw from an extensive wealth of observational and model data sets. Sources are always acknowledged in the captions, but I would like to express my gratitude for all of the observational teams, climate modeling groups (e.g., CMIP5) and government science agencies who ensure that such data sets are made freely accessible to the public.

Finally, I could not have written this book without the patience, love, and support of my family, to whom this book is dedicated: Alexis, Dean, and Caroline Karnauskas.