Introduction to

PHYSICAL OCEANOGRAPHY

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Introduction to Physical Oceanography

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Download the Book

These files are the latest version, August 13, 2008. The files are in Adobe Portable Document Format. This version has hyperlinked Table of Contents and Index for easier navigation of the document in Adobe Acrobat Reader. I thanks Andrew Kiss of the University of New South Wales in Canberra Australia for his help in using the \hyperref package to produce the links.

Book	Complete book in a 9.6 Mbyte file with index.
Cover	Color cover for your book.

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Introduction

This is a new textbook describing physical-oceanographic processes, theories, data, and measurements. In addition to the classical topics, I have included discussions of heat fluxes, the role of the ocean in climate, the deep circulation, equatorial processes including El Nino, data bases used by oceanographers, the role of satellites and data from space, ship-based measurements, and the importance of vorticity in understanding oceanic flows.

I have used the text to teach upper-division undergraduates and graduate students in oceanography, meteorology, and ocean engineering. Because many students have already taken courses that emphasize math, I have minimized the math and emphasized processes. Still, students should have studied differential equations and introductory college physics.

The text is typeset and it has high-resolution figures produced by Adobe Illustrator CS2. The book was produced in LATEX2ε using TeXShop 2.14 on an Intel dual-processor iMac running OS-X 10.4.11. The resulting typeset, 345 page, book.pdf file is only 9.5 Megabytes. If you make multiple copies I recommend you use a copy center that can make copies directly from the book.pdf file. These copies will be *much* better than copies made from printed pages.

If you have problems, please contact me at *stewart@ocean.tamu.edu*

Web Version

A web-based version the book is also available..

What's New!! Fall 2008 Revisions

This edition has a few minor and more important changes:

1. Corrected a few minor errors. There are less and less thanks to the many readers who have found errors in the

past.
2. Added information about the new Reference Salinity scale in Section 6.1.
3. Corrected an important error in my discussion of potential temperature in Section 6.5.
4. Added information about MODIS and Jason-2.
5. Removed references to controversy about vertical mixing in the ocean in Section 8.4. The controversy has been resolved.
6. Added more information about abrupt climate at end of the last ice age in Section 13.1.
7. Added more information about mixing driving the deep circulation in Section 13.3 and , and the role of Ekman pumping in the Antarctic and its influence on the deep circulation in Section 13.5
8. Added information about measured variability of the North Atlantic meridional overturning circulation in Section 13.4.
9. Removed information about solitons in Section 16.2. It is not that important in an introductory text that is alreay too long.

The table below links to the latest version of *Introduction to Physical Oceanography* in Adobe Acrobat Portable Document Format (pdf files). The files may be downloaded and printed if you wish a nice printed copy of the book. Altogether, there are viii + 345 pages in the book.

Fall 2007 Revisions

This edition has several changes from the previous edition. The changes include:

1. Mostly many small changes and corrections of minor errors. I thank all of you who have emailed comments to me this year.
2. COADS has been changed to the new ICOADS.
3. Revised section on definition of salinity to separate definition from extensions of definition to typical temperatures found in the ocean.
4. Revised section on temperature to refer to the new Smith and Reynolds Improved Optimal Interpolation scheme.
5. Added information on Prandtl's discovery of the boundary layer and its importance to oceanography
6. Revised paragraphs on altimeter errors to include more accurate values now being achieved for Jasin and Topex/Poseidon.
7. Revised figure 12.7 to show western intensification.
8. Clarified importance of equatorial heating for atmospheric circulation, and role of el Nino.
9. Added information on the Advanced Circulation Model for coastal processes and storm surges.

Fall 2006 Revisions

This edition has several changes from the previous edition. The changes include:

1. Updated information on maps of seafloor features and global bathymetric maps.
2. Revised section on measurements of winds to better describe satellite measurements of winds.
3. Revised section on measurements of currents to state more clearly the important techniques and drop less important information.
4. Dropped the description of fresh-water transports. I think the topic is beyond the scope of the book.
5. Made a few minor changes in wording and corrected a very small number of typographical errors. I thank all of you who have found almost all errors in previous years.
6. As a result, the book is one page shorter this year.

Fall 2005 Revisions

The files below are the latest version, August 10, 2005.

This edition has only minor changes from the previous edition. The changes include:

1. Clarified the discussion of important forces in Chapter 7.
2. Dropped all statements that a derivation is simple. It may be simple to some, but not to many students.
3. Added a new figure on Ekman flow in Chapter 9.
4. Revised the discussion of flow into and out of the Mediterranean Sea in Chapter 7.

5. Made a few minor changes in wording and corrected a few typographical errors.

Fall 2004 Revisions

This edition has only minor changes from the previous edition. The changes include:

1. Deleted all references to the practical salinity unit (psu). It doesn't exist. Salinity is a dimensionless ratio of masses.
2. Clarified the derivation of Margules' equation on page 171.
3. Made a few minor changes in wording and corrected a few typographical errors.

Spring 2004 Revisions

This edition has only minor changes from the previous edition. The changes include:

1. Revision of discussion of using vorticity to explain western boundary currents on page 204-205.
2. Changed explanation of tide generating forces on page 301.
3. Corrected error in equations describing the Ekman layer on page 139.
4. Corrected errors in figure 3.2.
5. Clarified differences between a surface analysis and reanalyzed weather data on pages 47.
6. Made a few minor changes in wording and corrected a few typographical errors.

Fall 2003 Revisions

The important changes include:

1. Many figures have been redrawn, some have been replaced.
2. The index is much improved.
3. Many references have been deleted or added. The calls to references in the text now agree with references at the end of the book.
4. Chapter 13 on the deep circulation has been revised to include recent advances in our understanding of the deep mass flow. Out is any reference to the thermohaline circulation (it is used in too many conflicting ways). In is the information that the deep flow is driven by wind and tidal mixing.
5. Hundreds of minor revisions throughout the book.

Fall 2002 Revisions

The important changes include:

1. We have an index! Trey Morris, a student, spent the summer tagging all the LaTeX files used to make the book. From these we produced an index and the pdf files below.
2. Don Johnson, another student, spent months redrawing many figures.
3. I simplified some of the discussions of errors. I found that students jumped to the conclusion that if there were several sources of error, no matter how small, the data were essentially worthless. This shortened the book by seven pages.
4. I made hundreds of small changes to the text.

Spring 2002 Revisions

The important changes include:

1. Gradually replacing poor scanned images with newly redrawn figures.
2. Corrected some significant errors in Chapter 10: tables had wrong values in one column, and text describing how currents are calculated from measurements of density was confusing
3. Many minor changes in all chapters.
4. The book is one page longer.
5. Adobe index file added.

Fall 2001 Revisions

The important changes include:

1. A beautiful cover.
2. Clarified the values for vertical diffusivity removing the conflict between Munk's value and measurements.
3. Revised the discussion of Ekman pumping and the role of vorticity in section 12.3.
4. Revised section 6.5 on density.
5. Added a description of neutral density.
6. Revised or redrew many figures.
7. Corrected many, many typos and other minor irritating errors.
8. The book is a few pages shorter.
9. Plus, I learned more about Adobe Illustrator 9 and Distiller 5 than I ever wanted to know. My testing leads me to believe the pdf files will print correctly.

Fall 2000 Revisions

I have revised many sections of the book, added new figures illustrating key concepts, and corrected many small errors. The important changes include:

1. More information on double diffusion.
2. Much revised section on Ekman currents.
3. Added description of the North Atlantic circulation in chapter 10, including discussion of the Gulf Stream and negative viscosity.
4. Clarified that vertical mixing drives the deep circulation, and added a description of the Antarctic Circumpolar Current in Chapter 13.
5. Revised discussion of El Nino/La Nina.
6. Dropped the old Chapter 15 on the observed circulation of the ocean and added the information to other chapters.

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September 2008 Edition

Contents

Preface

This book is written for upper-division undergraduates and new graduate students in meteorology, ocean engineering, and oceanography. Because these students have a diverse background, I have emphasized ideas and concepts more than mathematical derivations.

Unlike most books, I am distributing this book for free in digital format via the world-wide web. I am doing this for two reasons:

1. Textbooks are usually out of date by the time they are published, usually a year or two after the author finishes writing the book. Randol Larson, writing in *Syllabus*, states: "In my opinion, technology textbooks are a waste of natural resources. They're out of date the moment they are published. Because of their short shelf life, students don't even want to hold on to them"—(Larson, 2002). By publishing in electronic form, I can make revisions every year, keeping the book current.

2. Many students, especially in less-developed countries cannot afford the high cost of textbooks from the developed world. This then is a gift from the US National Aeronautics and Space Administration NASA to the students of the world.

Acknowledgements

I have taught from the book for several years, and I thank the many students in my classes and throughout the world who have pointed out poorly written sections, ambiguous text, conflicting notation, and other errors. I also thank Professor Fred Schlemmer at Texas A&M Galveston who, after using the book for his classes, has provided extensive comments about the material.

I also wish to thank many colleagues for providing figures, comments, and helpful information. I especially wish to thank Aanderaa Instruments, Bill Allison, Kevin Bartlett, James Berger, Gerben de Boer, Daniel Bourgault, Don Chambers, Greg Crawford, Thierry De Mees, Richard Eanes, Peter Etnoyer, Tal Ezer, Gregg Foti, Nevin S. Fučkar, Luiz Alexandre de Araujo Guerra, Hazel Jenkins, Jody Klymak, Judith Lean, Christian LeProvost, Brooks Martner, Nikolai Maximenko, Kevin McKone, Mike McPhaden, Thierry De Mees, Pim van Meurs, Gary Mitchum, Joe Murtagh, Peter Niiler, Nuno Nunes, Ismael Núñez-Riboni, Alex Orsi, Kym Perkin, Mark Powell, Richard Ray, Joachim Ribbe, Will Sager, David Sandwell, Sea-Bird Electronics, Achim Stoessel, David

Stooksbury, Tom Whitworth, Carl Wunsch and many others.

Of course, I accept responsibility for all mistakes in the book. Please send me your comments and suggestions for improvement.

Figures in the book came from many sources. I particularly wish to thank Link Ji for many global maps, and colleagues at the University of Texas Center for Space Research. Don Johnson redrew many figures and turned sketches into figures. Trey Morris tagged the words used in the index.

I especially thank NASA's Jet Propulsion Laboratory and the Topex/Poseidon and Jason Projects for their support of the book through contracts 960887 and 1205046.

Cover photograph of the resort island of Kurumba in North Male Atoll in the Maldives was taken by Jagdish Agara (copyright Corbis). Cover design is by Don Johnson.

The book was produced in LaTeX 2$_\varepsilon$ using TeXShop 2.14 on an Intel iMac computer running OS-X 10.4.11. I especially wish to thank Gerben Wierda for his very useful i-Installer package that made it all possible, and Richard Koch, Dirk Olmes and many others for writing the TeXShop software package. Their software is a pleasure to use. All figures were drawn in Adobe Illustrator.

Chapter 1

A Voyage of Discovery

The role of the ocean on weather and climate is often discussed in the news. Who has not heard of El Niño and changing weather patterns, the Atlantic hurricane season and storm surges? Yet, what exactly is the role of the ocean? And, why do we care?

1.1 Why study the Physics of the ocean?

The answer depends on our interests, which devolve from our use of the ocean. Three broad themes are important:

1. We get food from the ocean. Hence we may be interested in processes which influence the sea just as farmers are interested in the weather and climate. The ocean not only has weather such as temperature changes and currents, but the oceanic weather fertilizes the sea. The atmospheric weather seldom fertilizes fields except for the small amount of nitrogen fixed by lightning.
2. We use the ocean. We build structures on the shore or just offshore. We use the ocean for transport. We obtain oil and gas below the ocean. And, we use the ocean for recreation, swimming, boating, fishing, surfing, and diving. Hence we are interested in processes that influence these activities, especially waves, winds, currents, and temperature.
3. The ocean influence the atmospheric weather and climate. The ocean influence the distribution of rainfall, droughts, floods, regional climate, and the development of storms, hurricanes, and typhoons. Hence we are interested in air-sea interactions, especially the fluxes of heat and water across the sea surface, the transport of heat by the ocean, and the influence of the ocean on climate and weather patterns.

These themes influence our selection of topics to study. The topics then determine what we measure, how the measurements are made, and the geographic areas of interest. Some processes are local, such as the breaking of waves on a beach, some are regional, such as the influence of the North Pacific on Alaskan weather, and some are global, such as the influence of the ocean on changing climate and global warming.

If indeed, these reasons for the study of the ocean are important, lets begin a voyage of discovery. Any voyage needs a destination. What is ours?

1.2 Goals

At the most basic level, I hope you, the students who are reading this text, will become aware of some of the major conceptual schemes (or theories) that form the foundation of physical oceanography, how they were arrived at, and why they are widely accepted, how oceanographers achieve order out of a random ocean, and the role of experiment in oceanography (to paraphrase Shamos, 1995: p. 89).

More particularly, I expect you will be able to describe physical processes influencing the ocean and coastal regions: the interaction of the ocean with the atmosphere, and the distribution of oceanic winds, currents, heat fluxes, and water masses. The text emphasizes ideas rather than mathematical techniques. I will try to answer such questions as:

1. What is the basis of our understanding of physics of the ocean?
   (a) What are the physical properties of sea water?
   (b) What are the important thermodynamic and dynamic processes influencing the ocean?
   (c) What equations describe the processes and how were they derived?
   (d) What approximations were used in the derivation?
   (e) Do the equations have useful solutions?
   (f) How well do the solutions describe the process? That is, what is the experimental basis for the theories?
   (g) Which processes are poorly understood? Which are well understood?

2. What are the sources of information about physical variables?
   (a) What instruments are used for measuring each variable?
   (b) What are their accuracy and limitations?
   (c) What historic data exist?
   (d) What platforms are used? Satellites, ships, drifters, moorings?

3. What processes are important? Some important process we will study include:
   (a) Heat storage and transport in the ocean.
   (b) The exchange of heat with the atmosphere and the role of the ocean in climate.
   (c) Wind and thermal forcing of the surface mixed layer.
   (d) The wind-driven circulation including the Ekman circulation, Ekman pumping of the deeper circulation, and upwelling.

(e) The dynamics of ocean currents, including geostrophic currents and the role of vorticity.
(f) The formation of water types and masses.
(g) The deep circulation of the ocean.
(h) Equatorial dynamics, El Niño, and the role of the ocean in weather.
(i) Numerical models of the circulation.
(j) Waves in the ocean including surface waves, inertial oscillations, tides, and tsunamis.
(k) Waves in shallow water, coastal processes, and tide predictions.

4. What are a few of the major currents and water masses in the ocean, and what governs their distribution?

1.3 Organization

Before beginning a voyage, we usually try to learn about the places we will visit. We look at maps and we consult travel guides. In this book, our guide will be the papers and books published by oceanographers. We begin with a brief overview of what is known about the ocean. We then proceed to a description of the ocean basins, for the shape of the seas influences the physical processes in the water. Next, we study the external forces, wind and heat, acting on the ocean, and the ocean's response. As we proceed, I bring in theory and observations as necessary.

By the time we reach chapter 7, we will need to understand the equations describing dynamic response of the ocean. So we consider the equations of motion, the influence of earth's rotation, and viscosity. This leads to a study of wind-driven ocean currents, the geostrophic approximation, and the usefulness of conservation of vorticity.

Toward the end, we consider some particular examples: the deep circulation, the equatorial ocean and El Niño, and the circulation of particular areas of the ocean. Next we look at the role of numerical models in describing the ocean. At the end, we study coastal processes, waves, tides, wave and tidal forecasting, tsunamis, and storm surges.

1.4 The Big Picture

The ocean is one part of the earth system. It mediates processes in the atmosphere by the transfers of mass, momentum, and energy through the sea surface. It receives water and dissolved substances from the land. And, it lays down sediments that eventually become rocks on land. Hence an understanding of the ocean is important for understanding the earth as a system, especially for understanding important problems such as global change or global warming. At a lower level, physical oceanography and meteorology are merging. The ocean provides the feedback leading to slow changes in the atmosphere.

As we study the ocean, I hope you will notice that we use theory, observations, and numerical models to describe ocean dynamics. *None is sufficient by itself.*

1. Ocean processes are nonlinear and turbulent. Yet we don't really understand the theory of non-linear, turbulent flow in complex basins. Theories used to describe the ocean are much simplified approximations to reality.
2. Observations are sparse in time and space. They provide a rough description of the time-averaged flow, but many processes in many regions are poorly observed.
3. Numerical models include much-more-realistic theoretical ideas, they can help interpolate oceanic observations in time and space, and they are used to forecast climate change, currents, and waves. Nonetheless, the numerical equations are approximations to the continuous analytic equations that describe fluid flow, they contain no information about flow between grid points, and they cannot yet be used to describe fully the turbulent flow seen in the ocean.

By combining theory and observations in numerical models we avoid some of the difficulties associated with each approach used separately (figure 1.1). Continued refinements of the combined approach are leading to ever-more-precise descriptions of the ocean. The ultimate goal is to know the ocean well enough to predict the future changes in the environment, including climate change or the response of fisheries to over fishing.

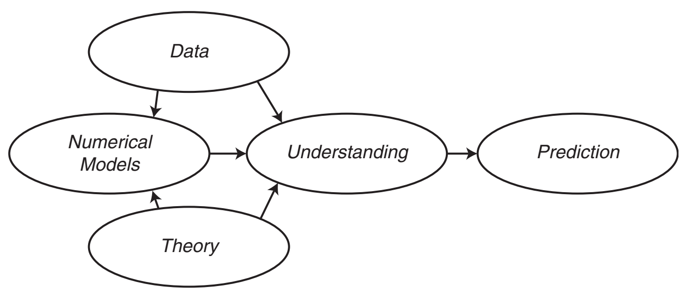

Figure 1.1 Data, numerical models, and theory are all necessary to understand the ocean. Eventually, an understanding of the ocean-atmosphere-land system will lead to predictions of future states of the system.

The combination of theory, observations, and computer models is relatively new. Four decades of exponential growth in computing power has made available desktop computers capable of simulating important physical processes and oceanic dynamics.

> All of us who are involved in the sciences know that the computer has become an essential tool for research . . . scientific computation has reached the point where it is on a par with laboratory experiment and mathematical theory as a tool for research in science and engineering—Langer (1999).

The combination of theory, observations, and computer models also implies a new way of doing oceanography. In the past, an oceanographer would devise a theory, collect data to test the theory, and publish the results. Now, the tasks have become so specialized that few can do it all. Few excel in theory, collecting data, and numerical simulations. Instead, the work is done more and more by teams of scientists and engineers.

1.5 Further Reading

If you know little about the ocean and oceanography, I suggest you begin by reading MacLeish's (1989) book *The Gulf Stream: Encounters With the Blue God*, especially his Chapter 4 on "Reading the ocean." In my opinion, it is the best overall, non-technical, description of how oceanographers came to understand the ocean.

You may also benefit from reading pertinent chapters from any introductory oceanographic textbook. Those by Gross, Pinet, or Segar are especially useful. The three texts produced by the Open University provide a slightly more advanced treatment.

Gross, M. Grant and Elizabeth Gross (1996) *Oceanography—A View of Earth.* 7th edition. Prentice Hall.

MacLeish, William (1989) *The Gulf Stream: Encounters With the Blue God.* Houghton Mifflin Company.

Pinet, Paul R. (2006) *Invitation to Oceanography.* 4nd edition. Jones and Bartlett Publishers.

Open University (2001) *Ocean Circulation.* 2nd edition. Pergamon Press.

Open University (1995) *Seawater: Its Composition, Properties and Behavior.* 2nd edition. Pergamon Press.

Open University (1989) *Waves, Tides and Shallow-Water Processes.* Pergamon Press.

Segar, Douglas A. (2007) *Introduction to Ocean Sciences.* 2nd edition. W. W. Norton.