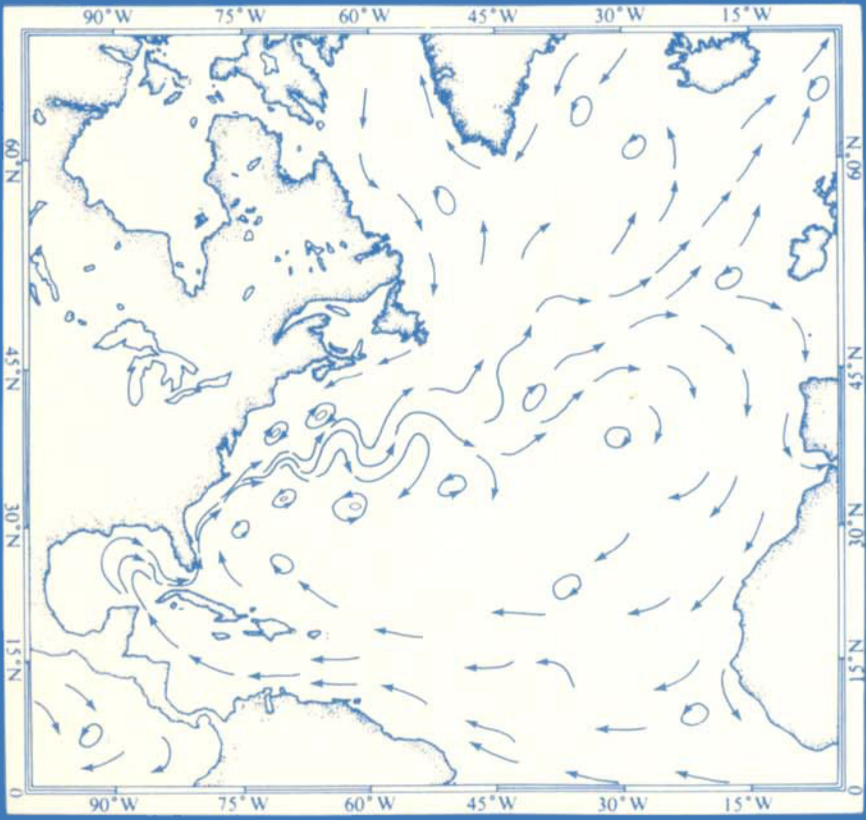
INTERNATIONAL GEOPHYSICS SERIES • VOLUME 38

Principles of Ocean Physics

J. R. Apel



Principles of Ocean Physics

This is Volume 38 in
INTERNATIONAL GEOPHYSICS SERIES
A series of monographs and textbooks
Edited by RENATA DMOWSKA and JAMES R. HOLTON
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Principles of Ocean Physics

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ACADEMIC PRESS

A Harcourt Science and Technology Company

San Diego San Francisco New York
Boston London Sydney Tokyo

This book is printed on acid-free paper.

Fifth printing 1999

Academic Press
24–28 Oval Road, London NW1 7DX, UK
http://www.hbuk.co.uk/ap/

Academic Press
A Harcourt Science and Technology Company
525 B Street, Suite 1900, San Diego, California 92101-4495, USA
http://www.apnet.com

ISBN 0-12-058865-X
ISBN 0-12-058866-8 (Pbk)

Apel, J. R.
Principles of ocean physics. – (International geophysics series, ISSN 0074-6142)
1. Oceanography
I. Title II. Series
551.46′01 GC150.5
LCCCN 87-70490
LCCCN 87-70489 (Pbk)

Printed in Great Britain by St Edmundsbury Press Ltd, Bury St Edmunds, Suffolk
00 01 02 03 SE 9 8 7 6 5

Preface

The study of the physics of the sea has been somewhat detached from the study of physics *per se;* even its common name of physical oceanography reveals an alliance with geography that is as strong as that with physics. In recent years, however, significant advances in both the theoretical and observational sides of the discipline have allowed more quantitative descriptions of the physical behavior of the ocean to be derived. As a result, it becomes possible to carry on much discourse in physical oceanography in the traditional language of physics, that is, in terms of processes and mechanisms clothed in the idealized garb of equations, numbers, and graphs.

This is not to say that all is known of the physics of the sea, or that descriptive physical oceanography no longer has a role – far from it. The real world is much too complicated for either of these statements to be true. It is simply that the subject has happily progressed to a point where the unification and synthesis resulting from a deepened physical understanding no longer have the associated risk of simplification *ad absurdum* that they once might have had.

The preparation of this book was originally undertaken in the hope that it might stimulate a few physics graduate students to the serious study of the oceans, perhaps even as a life's work. To the extent that it has provided any such migration across disciplines, the book will have served its purpose. In writing it, I have tried to address the nonexpert but reasonably mature physical scientist who might like to know something of the fundamentals of the quantitative physics of the sea without being put off by having to read introductory student texts, or diverted by the focus and detail of the research literature. In this audience I would count working physicists, graduate students, and perhaps even an occasional scientist from an allied discipline (i.e., dynamics, electromagnetics, optics, and the like) who is interested in the marine environment. In doing so, however, I have tried to present a viewpoint that a physical oceanographer might not object to, and have attempted to use his or her language alongside our common tongue of physics. In this way the book may also serve as a lexicon, giving the reader access to the information shrouded by such mysteries as "quasi-geostrophic motions in baroclinic instability" or "conservation of potential vorticity." In discussing a process or a mechanism, I have first tried to describe it and then to account for it theoretically, if possible. Purely deductive reasoning from equations is often not rewarding in a subject as complicated as this. I have also freely used results from numerical models, laboratory experiments, and remote measurements, in addition to the classical sources of observations made in the water and calculations made with theory. The text has not attempted to be exhaustive, but rather to present the fundamentals with what is hoped to be a balanced perspective. Enough access is provided to more advanced or specialized texts so that the reader can eventually find a way into the research literature, if desired.

The untimely deaths of two colleagues occurred while I was readying this manuscript for publication, and their passings have deprived the field of two of its most able and productive scientists. Those familiar with Prof. Adrian Gill's excellent monograph, *Atmosphere-Ocean Dynamics,* will recognize the large intellectual debt owed to that work by the sections of this book concerned with geophysical fluid dynamics. In quite another discipline, Dr. Rudolph Preisendorfer put the field of optical oceanography on a firm mathematical basis with the publication of his four-volume work, *Hydrologic Optics,* on which Chapter 9 draws so heavily. Because of the inspiration that their research and writing have provided to the community, and their importance in my own efforts, I dedicate this text to A. E. Gill and R. W. Preisendorfer. I also dedicate it to those five fathers of modern physical oceanography whose names appear so frequently here: H. U. Sverdrup, C.-G. Rossby, V. W. Ekman, H. M. Stommel, and W. H. Munk, all teachers as well as researchers.

In the Revised Edition, a number of errors have been corrected, notation has been made more uniform, and a few recent references have been added.

J.R.A.
Manor Park, Maryland

Acknowledgments

In a book of this length and novelty, it is inevitable that errors—be they conceptual, calculational, or typographical—will be present. I am grateful to colleagues who reviewed portions of the manuscript in response to appeals for assistance in reducing its error rate to acceptable levels; they included Roswell Austin, Robert Beal, Jack Calman, Janet Campbell, Nicholas Fofonoff, Richard Gasparovic, Howard Gordon, Jimmy Larsen, Lawrence McGoldrick, Owen Phillips, Charles Schemm, Morris Schulkin, Donald Thompson, Kenneth Voss, Robert Winokur, Warren Wooster, and Charles Yentsch. The remaining errors (ever too numerous) are clearly my responsibility. It is also with thanks that I acknowledge the patience of my students, who were exposed to the early drafts of the text and who suffered in unknown ways as a result of its imperfections.

I am especially appreciative of the support given by The Johns Hopkins University Applied Physics Laboratory in the award of a Stewart S. Janney Fellowship, which allowed me to convert a draft manuscript into a finished publication; and in the editorial, illustrations, and typesetting functions carried out by the Laboratory staff. A number of associates assisted in this regard, and special thanks go to my editor, Al Brogdon; my editorial assistants, Linda Muegge and Jacqueline Apel; artists Mary O'Toole and Stephen Smith; secretaries Anne Landry, Barbara Goldsmith, and Jeaneen Jernigan; and compositors Veronica Lorentz, Patrice Zurvalec, Barbara Bankert, Nancy Zepp, Sandy Bridges, Barbara Northrop, and Brenda Laub. The encouragement and assistance of Academic Press, especially of Conrad Guettler, are gratefully acknowledged.

JOHN R. APEL

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Why did the old Persians hold the sea holy?
Why did the Greeks give it a separate deity, an own brother of Jove?
Surely all this is not without meaning.

Melville, *Moby Dick*

Chapter One

Physical Oceanography: An Overview

The history of science is science itself; the history of the individual, the individual.

Goethe, *Mineralogy and Geology*

1.1 Introduction

The study of the physics of the sea is the study of a broad range of classical and modern physics as applied to a complicated and pervasive medium covering much of the earth. The subject is properly a branch of geophysics, although that term is often applied in a more narrow sense to the physical characteristics of the solid earth; we shall not so restrict it here.

Ocean physics, which grew out of both the physical geography of the sea and meteorology, appears to have diverged from the mainstream of the discipline sometime around the turn of this century, when the attention of basic researchers in physics became increasingly directed toward the atomic and subatomic nature of matter. However, in the hands of northern European scientists who, to some extent, were conditioned by the need for solving maritime and fisheries problems, the subject of physical oceanography led a limited but vigorous existence under the *nom de choix* of hydrography, as it is known in those quarters even today. In North America the more common name of physical oceanography has been used, while in the USSR the preferred terminology is physical oceanology.

The growth of ocean physics has been stimulated not only by its intellectual character and by the practical needs of maritime affairs, but also by the slowly growing realization that the ocean plays an enormously important role in conditioning both weather and climate, over land and sea alike. The exploitation of this awareness, however, has at the same time been severely limited by the lack of an adequate data base that would allow one to construct a dynamical picture of physical events in the sea.

Atmospheric science has made significant contributions to the subdiscipline of fluid dynamics of the sea. The exigencies of producing a daily forecast of weather long ago drove scientists and nations to erect what has become a synoptic scale (approximately 250 km) weather-observing network over essentially all of the land areas of the Northern Hemisphere, and a considerably more rarefied system over the Southern Hemisphere and the oceans. More importantly, this network has provided data leading to dynamical concepts that appear to explain atmospheric processes on an extremely wide range of space and time scales. There currently exist reasonably quantitative theoretical and numerical explanations of events in the atmosphere ranging from tornadoes to the general circulation of the earth's atmosphere. The scales of these events span dimensions of the order of 5 km at the small end to 5×10^5 km at the large.

The realization that the dynamics of the atmosphere might be translated into the dynamics of the ocean with appropriate changes in scaling factors occurred over a period of years before, during, and after World War II. While the data base to verify the validity of these similarity transformations and changes in boundary conditions is as of now only partially assembled, enough has been done to give one confidence that the subject of geophysical fluid dynamics, as it has come to be known, is on firm ground for both the atmosphere and the ocean. Indeed, it has even been applied with varying degrees of success to the motion of the atmospheres of Venus and Jupiter. This success does not imply that all is known about ocean dynamics, but only that the basic framework is intact. The problems arise because many processes taking place in the ocean are so complicated and span such a range of scales that their reasonably rigorous description in terms of first principles exceeds all available computational power. The analyst is then forced to *parameterize* many of the processes, i.e., replace their rigorous physical descriptions with a simplified model whose adequacy is often difficult to assay. (An example of a widely used parameterization is the treatment of large-scale turbulence in terms of a relatively simple eddy diffusion process; this is discussed in the chapters on hydrodynamics and geophysical fluid dynamics.) Parameterization is essential for real progress to be made in geophysics.

While fluid dynamics was probably the branch of physics first finding significant application to the sea (and it is still the dominant one), it is by no means the sole subdiscipline. Thermodynamics and its characterization of matter by bulk properties such as an equation of state was also an early entry. Underwater acoustics is relevant because it is the only known form of signaling that can carry information through large distances in the sea—a fact of much interest to submarine warfare, to the study of marine life, and to charting the ocean depths. Electromagnetism finds application through the measurement of voltages induced by the conducting sea water moving in the earth's magnetic field, as well as through the techniques of remote measurement of sea surface properties via radio and microwave probing. The study of optics of the sea has been stimulated by the need to understand absorption or emission of infrared, visible, and ultraviolet radiation, which in turn are relevant to the life cycle of flora and fauna and to the interchange of heat and water vapor between the sea and the atmosphere. The detailed description of the earth's gravity and geoidal fields finds application in relatively subtle ways in the establishment of mean sea level and in the dynamics of large-scale currents. Geology and solid earth geophysics concern themselves with the basins that contain the oceans, with the crust moving on global but geological time scales that imply that ancient oceans were quite different in many ways from the present ones. The atomic and molecular physics of the constituents of seawater largely determine the macroscopic properties of the medium with which the oceanographer so unconcernedly deals. At a smaller level still, nuclear physics in the sea is in part occupied with the migration of radioactive materials, with nuclear radiation, and with the behavior of reactor neutrons from ships.

These, then, are the subject areas of the physics of the sea.

1.2 The Evolution of Modern Physical Oceanography

It is abundantly clear that the origins of the scientific study of the ocean are to be found in the sailing and navigational needs of the sea-going commerce that took place among the Mediterranean countries of the ancient world and which later included those of the Far East. Piloting and navigation as arts (rather than sciences) have been practiced by sailors for some 6000 to 8000 years, using the accumulated knowledge of the sea and its winds, waves, and currents. This understanding was passed on by a combination of (1) tutelage before the mast, where its imperfections were often punctuated by finding one's vessel *in extremis* due to poor navigation or sudden bad weather, and (2) in maritime schools, where master seamen and scholars perpetuated what was then known—or thought—about the sea and its navigation. Even at that stage, there were close interactions between sailors returning from a voyage and reporting their observations to their sponsors, and scholars who, with varying degrees of success, would attempt to fit those observations together with others to form some sort of world view. On occasion a scholar would even go to sea and experience its wonders personally, a practice that is not followed frequently enough even today.

In the Greco-Roman world, maritime charts often contained summaries of what was known about both the geography of the Mediterranean region and its navigation. The earliest surviving map of the region showing quantitative character is due to Eratosthenes (ca. 250 B.C.), who used lines of latitude and longitude and the 16-point wind rose on his chart of the then-known world. He also determined the circumference of the earth with considerable accuracy by comparing the length of a shadow in Alexandria at high noon on the summer solstice with the observation, on the same day, of the exact vertical illumination of a well located on the Tropic of Cancer; the value he obtained was about 43,000 km. In the second century A.D., Claudius Ptolmey published an outstanding world map that used a conic projection; however, Ptolmey apparently ignored Eratosthenes' value for the circumference of the earth and instead used a lesser value of approximately 32,000 km. So influential was Ptolmey's cartography that, upon the rediscovery and translation from Greek to Latin of his *Cosmographia,* the Renaissance navigators (including Columbus) easily became convinced that the distance around the world was only some 75% of its actual circumference. This error was not generally rectified until the late 1600's.

Along with the charts and maps were produced *sailing directions* containing information on distances, aids and dangers, and characteristics of the sea, the earliest of which dates from sometime between the sixth and fourth centuries B.C. The practice of publishing these volumes has continued to the present, with considerable improvements being made by 16th century navigators and scholars. For a time both charts and sailing directions were bound together, but increasing knowledge as time went on made these documents so bulky that they eventually came to be published as separate entities. These directions contained much of what was known of the physical oceanography of the day. It is fair to say, though, that there was no organized body of knowledge known by that name until the 19th century, and such knowledge as existed was in the province of the navigator as much as the scholar.

The beginnings of modern navigation and scientific study of the sea are probably marked by the three Pacific voyages of Captain James Cook of the British Royal Navy between 1768 and 1779. Among the array of other scientific instruments, his parties carried chronometers that allowed the precision determination of time and longitude and, hence, the positions of land masses, reasonable estimates of ship's positions, and the influence of currents on those positions. With the completion of Cook's voyages and the publication of the findings in several volumes and journals, the major dimensions of the world's oceans were known and the first glimmerings of the science of the sea were apparent.

During the same general time period, Benjamin Franklin, then Postmaster General of the United States, prepared a surprisingly accurate chart of the path of the Gulf Stream by compiling reports of the drift of ships plying the waters between Britain and the United States. This chart enabled American ships to reduce the round-trip time to England over their British competitors by several days, by riding the Gulf Stream while going east and avoiding it when returning. Modern vessels make use of updated, more accurate versions of the same information.

The H.M.S. *Beagle* expedition of 1831–36 with Charles Darwin as naturalist is considered the next major oceangoing campaign to intensively study environmental sciences, this time with a concentration on regions of the Southern Hemisphere. While more directed toward biological and geological studies than physics as such, its scientific orientation and the breadth of its scientific party ensured that there would be contributions to a range of disciplines. Darwin's conclusions on species variability are well known, but his first-hand observations of mountain building in the Andes and his theories on coral reef formation and seamount subsidence laid the groundwork for much later concepts of the dynamics of the earth's crust. The publication of his *Journal of Researches* in 1845 predates his *Origin of Species* by 14 years.

While organized knowledge derived from expeditions of the types just described was highly valuable to the advance of science, the example of Franklin's Gulf Stream chart nevertheless demonstrated the utility of ships' navigational and meteorological data in ocean studies. In the hands of Lt. Matthew F. Maury, an American naval officer, this type of analysis reached its pinnacle. Confined to limited duty by an injury, he was placed in charge of the Naval Depot of Charts and Instruments in 1842, where he had access to ships' log books and other records. He quickly realized the enormous value of the information in them and, over the next few years, subjected the data to analyses that yielded currents, winds, and shipping routes throughout much of the world's oceans. His publication of charts and sailing directions starting in 1849 caught the attention of seafarers throughout the world and led to an international cooperative effort in collecting marine data at regular intervals that persists today with some modification. Chapter I of Maury's 1855 book entitled *The Physical Geography of the Sea* opens with the paragraph:

> THERE is a river in the ocean. In the severest droughts it never fails, and in the mightiest floods it never overflows. Its banks and its bottom are of cold water, while its current is of warm. The Gulf of Mexico is its fountain, and its mouth is in the Arctic Seas. It is the Gulf Stream.

Figure 1.1 is a reproduction of Maury's chart of "Gulf Stream and Drift," which is both a scientific and an artistic masterpiece. Later work has added greatly to the understanding of this "river" (see Chapter 6), but none has come close to having the impact on ocean science of his pioneering work.

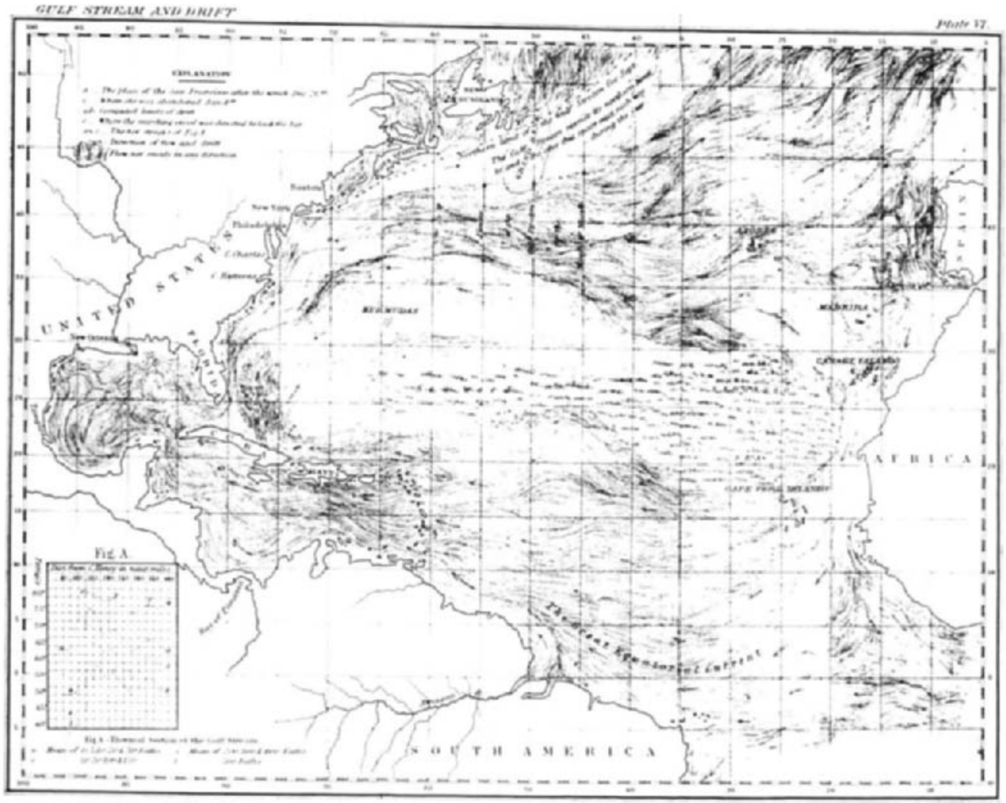

Fig. 1.1 Maury's chart, "Gulf Stream and Drift," showing flow lines as deduced from ship navigation reports, and surface temperature sections extending eastward from Virginia. [From Maury, M. F., *The Physical Geography of the Sea* (1855).]

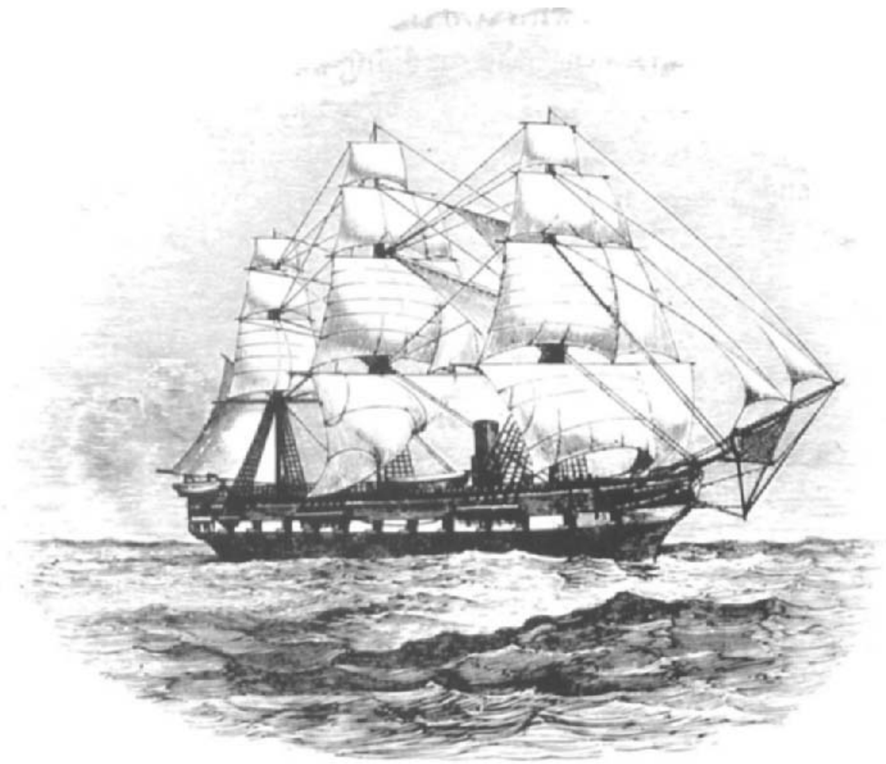

Fig. 1.2 Drawing of H.M.S. *Challenger* [From Thompson, C.W., *Voyage of the "Challenger"* (1878).]

Today, the analysis of century-old data from the "Marine Deck" continues to yield long-term trends in oceanography and meteorology. The collecting of global marine weather information at 6 hour intervals continues as well, now under the auspices of the World Meteorological Organization, and constitutes an essential data source for real-time numerical weather forecasts.

By the last third of the 19th century, a new force had come into play in the science of the sea: the transoceanic telegraph. The requirement for laying cable along the sea floor to join continents via communications links led nations to the realization that the physical, chemical, and biological conditions of the deep sea floor might well determine the success or failure of such ventures. The British Royal Society recommended that an expedition should survey the physical and biological state of the sea along certain sections, and H.M.S. *Challenger* (Fig. 1.2) was assigned to the task, with C. Wyville Thomson as director of the scientific staff. From 1872 to 1876, the ship surveyed major lines in three oceans in a series of research cruises that constituted

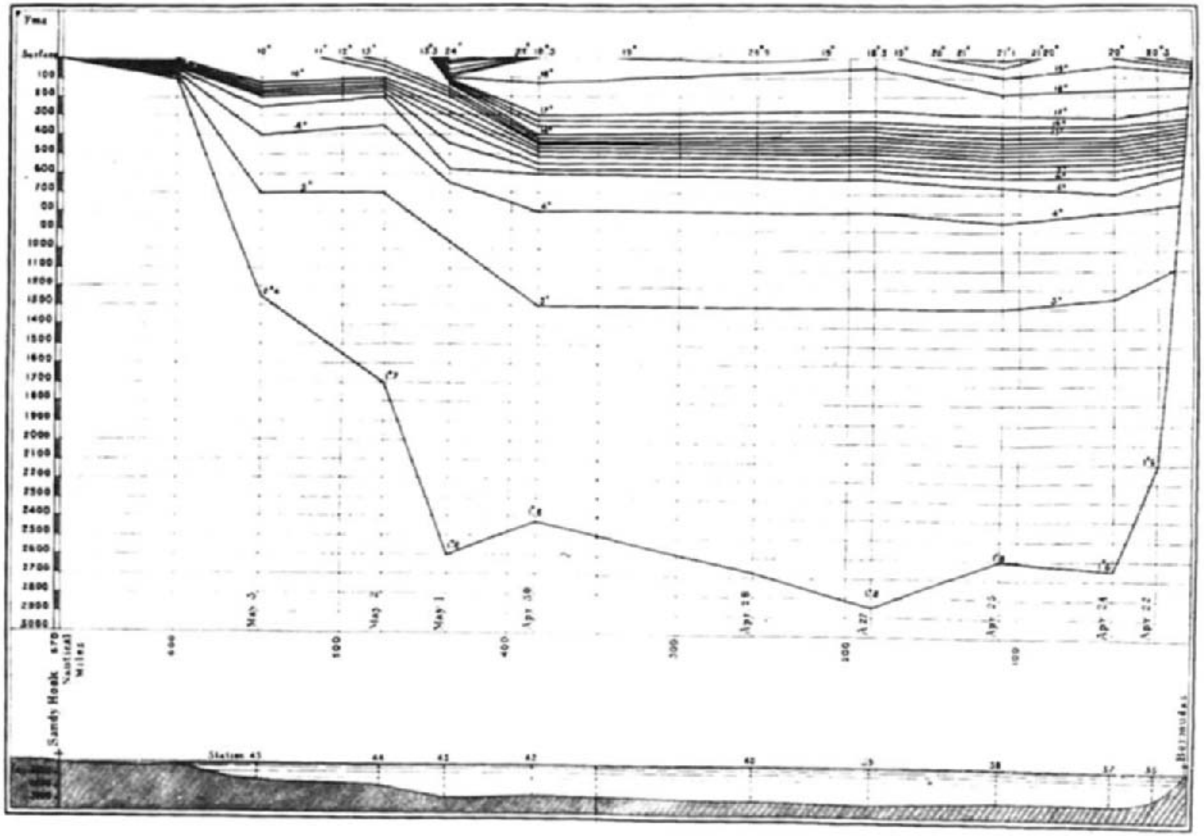

Fig. 1.3 Subsurface temperature profile from Bermuda to Sandy Hook, N.J., as obtained during the *Challenger* expedition in 1873. The presence of the northwestern boundary of the Gulf Stream is indicated by the steep slopes of the isotherms in the vicinity of stations 42-44. [From Thompson, C. W., *The Voyage of the "Challenger."* (1878).]

the first modern oceanographic expedition. Among the extensive new information developed and ultimately published in some 50 volumes were temperature and depth measurements and bottom samples that revealed oddities of the deep. A temperature section from Bermuda to Sandy Hook, N.J., is shown in Fig. 1.3, with the slopes of the isotherms showing the northwest boundary of the Gulf Stream near Stations 42 and 43. The dynamical significance of these data was probably not appreciated at the time, but such information would later allow oceanographers to compute the variation of current speeds with depth using the "dynamic method." It is probably fair to say that the *Challenger* expedition marked the beginnings of oceanography as a systematic scientific enterprise.

The one-third century between the *Challenger* expedition and the onset of World War I saw a flowering of both exploration and the academic, basic research phases of ocean science. It was a time of great public faith in the benefits of science and technology and in the ultimate "perfectibility of man," and the general scientific advances in theoretical understanding and in improved measurement capabilities led to concomitant advances in field oceanography. Exploration of the Arctic and Antarctic continued apace, with scientists as often as military officers leading exploration parties; in these, Scandinavian and Russian investigators figured prominently, with the most famous of the scientific polar expeditions being headed by F. Nansen during the three-year drift of the Norwegian vessel *Fram* through the Arctic Basin. On the academic side, basic developments in classical fluid dynamics were soon followed by their application to both meteorology and physical oceanography; for a time, the practitioners of the analytical parts of those sciences were generally theoretical physicists and applied mathematicians, with the names V. F. K. Bjerknes, V. W. Ekman, and V. J. Boussinesq frequently occurring in the literature. In chemistry, the physicochemical properties of seawater, especially its thermodynamics, were established with accuracies that allowed the quantitative interpretation of field data, an effort in which M. Knudsen figured prominently. In general, it was an era when the basics of the science were being uncovered through the interactions of exploration, field and laboratory measurement, and theoretical formulation. These methods continue to be the *modi operandi* of ocean science even today, but with the addition of large-scale numerical modeling as a major new ingredient not available to the earlier investigators.

During this time, there was an increasing understanding of the interrelationships among the physics, chemistry, and biology of the sea and of the importance of these sciences in the very practical requirements of commercial fisheries. Since edible fish are generally among the climax species in the oceanic food chain, the impacts of far-removed physical and chemical factors such as wind-driven surface currents, upper ocean temperatures, dissolved oxygen, and suspended particulates upon higher trophic levels in the marine ecosystem were only suspected to exist. The conviction that such factors are relevant but not well enough understood led to the establishment, in Copenhagen in 1902, of the International Council for the Exploration of the Sea, a unique treaty/scientific organization of North Atlantic states that continues today to foster research in these subjects.

World War I provided two additional stimuli for the study of the sea: the submarine, and the asdic, almost the sole means of detecting the submerged submarine. (Asdic evolved into the more familiar sonar, which reached operational use after the war.) Experiments by the British showed that the detectability of submarines by sonar was largely conditioned by the temperature and density structure of the upper ocean, and that correctly acquired measurements of thermal profiles were of considerable assistance in understanding and predicting the detection process. As with so many other inventions of engines of destruction, developments in antisubmarine warfare have had beneficial influences on nonmilitary oceanography, in that ocean instrumentation and theoretical comprehension have been significantly advanced as consequences of submarine-oriented studies. Today, a major portion of the basic oceanic research sponsored by the navies of the world has as its end objective the improved forecasting of marine environmental conditions for both submarine and surface ship operations.

The period between the two World Wars saw the growth of ocean research institutions and programs in almost all of the technologically advanced nations. New research vessels were commissioned and built by many, including *Meteor* by the German Navy in 1924, H.M.S. *Discovery* by the British in 1925, and R.V. *Atlantis* by the newly founded Woods Hole Oceanographic Institution in 1930. The Scripps Institution of Oceanography, while first organized in 1903, acquired its present name and was dedicated to research in 1925. The exponential-like growth that characterized research in other fields and which extended approximately from those years through to the 1960's also affected oceanography, although that subject started from a much smaller base. The discipline is still miniscule compared with, say, chemistry or physics (the *U.S. Directory of Marine Scientists* for 1987 listed about 6600 names active in all areas of marine science, compared with the approximately 60,000 members of the American Institute of Physics societies alone).

Stimulated by the events of World War II and the technologies that grew from it, the post-war oceanic sciences expanded greatly in breadth and depth, both literally and figuratively. The global nature of the conflict, which involved naval operations in waters around the world, led to increased demands for mapping and marine forecasts. Acoustic bathymetry (depth sounding) allowed rapid charting of regions untouched by the sounding lead line; ultimately these soundings, along with other geophysical measurements (e.g., of magnetics and gravity) gave rise to the theories of sea floor spreading and provided a mechanistic underpinning for the hypothesis of continental drift put forth by A. Wegener in 1915. By the mid-1960's, the plate tectonic theory was generally (but not universally) accepted by marine geologists and geophysicists (see Chapter 2). The submarine problem, too, had oceanographic by-products of importance in the understanding of upper ocean dynamics. The invention of the mechanical bathythermograph by Spilhaus and the follow-on development of expendable temperature, conductivity, and current probes significantly extended measurement capabilities in the upper several hundred meters of the sea. The installation of precision loran navigation near shore, and then the invention of satellite Doppler navigation by The Johns Hopkins University Applied Physics Laboratory allowed positioning accuracies of features at sea in the range of tens of meters. The successful deployment of deep water current meter and thermistor arrays for months on end became feasible because of the efforts of Woods Hole scientists, among others. Since oceanography has always been a data-starved science, these extensions of measurement capability and efficiency had great impact on the understanding of physical processes in the sea. A new round of ship construction after the war placed improved sea-going platforms at the disposal of the wet-deck oceanographer, although in the United States many of these ships are currently nearing the ends of their useful lives. An entirely different kind of ocean-viewing platform, the spacecraft, returned quite useful information via sensors not originally intended for observing the sea. Recent developments in dedicated satellite remote measurement, such as the determination of surface temperature, current velocity, wind stress, wave spectra, and the visualization of flow patterns with color images of the sea, are just now making serious impacts on the data-scarcity problem, and are probably still only in their embryonic state. Moored and drifting buoys carrying surface and near-surface instrumentation can forward their data and position through satellite communication links, returning information on the oceans with much efficiency.

Theoretical developments have accelerated as well, driven in part by the expanding data base resulting from such instrumentation, in part by the increased understanding of atmospheric dynamics that has diffused over into ocean dynamics, and to a very great degree by the availability of large computing resources. The last quarter-century has seen a significant movement of physical oceanography away from its origins in the physical geography of the sea toward a quantitative, hypothesis-testing kind of activity, in considerable degree because of the unifying theoretical concepts that have grown out of the accumulated body of information derived from the ocean research enterprise to date.

It is thus to a major degree that this book is directed toward the basic theoretical underpinnings of physical oceanography, viewed from a vantage point that holds the subject to be a subdiscipline of physics. To that end it is short on the descriptive and experimental sides of the ledger, and for reasons of length, on the applications of the basic concepts to a satisfactorily wide range of ocean problems. It is hoped that enough of the flavor of those problems has been included in the book for the reader's tastes to be stimulated toward further study.

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Chapter Two

Forcing Functions and Responses

First, they should have right ideas of things, ideas that are based on careful observation, and understand causes and effects and their significance correctly.

The Teaching of Buddha, Book 3, "The Way of Practice."

2.1 Introduction

In order to help the understanding of the more quantitative material found later in the book, this chapter is devoted to a description, in minimally mathematical format, of the major forces and constraints acting on the ocean, as well as the responses with which the sea acknowledges those nudgings and pullings. This description will make somewhat more clear why *dynamics* (i.e., the study of oceanic motions) forms such a major portion of the physics of the sea. This is not to give short shrift to the other subdisciplines of acoustics, optics, etc., for indeed, these are treated somewhat more fully than is usual in introductory texts on physical oceanography; it is only that the dynamics condition much of the state of the medium in which higher frequency wave propagation—be it acoustic, electromagnetic, or optic—takes place.

2.2 Forcing Functions On and In the Sea

It is convenient to divide the forces acting on the sea into a few classes, although as with all categorizations, there is more than one way to do this, and the categories are not necessarily mutually exclusive. In order of their scale and their usual appearance in the Navier–Stokes dynamical equations, they are: (1) gravitational and rotational forces, which permeate the entire fluid and which have large scales compared with most other forces; (2) thermodynamic forces, such as radiative transfer, heating, cooling, precipitation, and evaporation; (3) mechanical forcing, such as surface wind stress, atmospheric pressure variations, seismic sea floor motions, and other mechanical perturbations; (4) internal forces – pressure and viscosity – exerted by one portion of the fluid on its other parts, and which serve to make fluid dynamics much more complicated than single particle dynamics. In a somewhat separate category but overlapping the others to a degree is (5) boundary forcing, which on the bottom usually acts statically as a simple containment force, but which is generally formulated as boundary conditions on the equations. The fluid invariably acts to develop boundary layers in response to these – for example, the Ekman layer at the ocean surface, the benthic boundary layer at the bottom, and western and eastern boundary currents along the margins of the sea near continents.

2.3 Gravitational and Rotational Forces

If the volume of ocean water, V, of approximately 1.370×10^9 km^3 were uniformly distributed over a smooth, spherical earth with a mean radius, R_e, of 6371 km, it would have a mean depth of approximately 2700 m; since only 70.8% of the earth's surface is covered with water, however, the actual mean depth, H, is closer to 3800 m. The aspect ratio of the ocean is $H/2\pi R_e\sqrt{0.708} \approx 1 \times 10^{-4}$, which is approximately the same as the thickness-to-width ratio of the paper on which a typical chart of the world's oceans is printed. Relative to its breadth, then, the ocean is very shallow, and the force of gravity that maintains this thin sheet in place is very nearly, but not exactly, the value of the gravity at the solid surface of the earth.

The subject of marine gravity has some important implications not only for solid earth geophysics, but also for physical oceanography, as we shall see ahead, since small-scale variations in the magnitude and direction of the gravitational acceleration have observable consequences on the equipotential surface of the sea. In addition to the earth's gravity, clearly the moon and sun exert gravitational effects on the sea, these (plus spin, as will be discussed later) being the major tide-producing forces on both the solid earth and its fluid envelopes of air and water. Figure 2.1 is a schematic diagram of these gravitational and rotational forces. Such time-dependent forces are driven at exact astronomical frequencies and can be predicted with considerable precision for years in advance; tidal height forecasts are among the most successful operational predictions available for the sea.

Rotational forces also play a role in geophysical fluid dynamics, with three

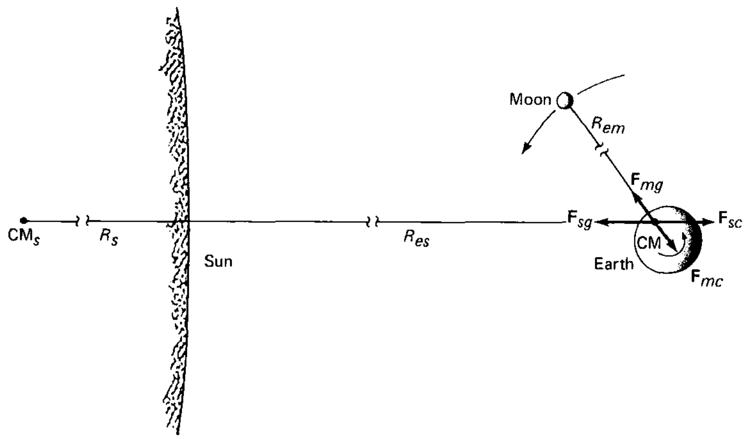

Fig. 2.1 Force diagram for the earth-moon-sun system. Tidal forces arise from both gravitational and centrifugal forces caused by the moon and the sun.

distinct motions contributing: (1) the earth's daily spin; (2) the rotation of the moon on a near-monthly period; and (3) the annual rotation of the earth-moon system about the common center of mass of the solar system. The centripetal acceleration and the concomitant flattening of the earth due to the first of these motions results in a variation of the effective surface gravity by approximately 0.52% from pole to equator. The other two rotations also produce centripetal accelerations that contribute to the tide-producing forces in a fashion that will be discussed in Chapters 3 and 5. There the gravitational and rotational forces will be mathematically summarized in terms of a potential function, Φ, whose negative gradient gives both forces.

2.4 Radiative, Thermodynamic, and Related Forces

The radiant energy that drives the earth's fluid envelopes comes from only two major sources: (1) the sun, as an external source; and (2) the decay of radioactive matter within the earth's interior, which maintains the material below the surface crust in either a plastic or a fluid condition (except for the inner, solid core). The latter energy influences, to a degree, the bottom temperature of the deep sea but is not an important source for dynamical effects.

The sun is approximately a graybody with an emissivity, e_λ, of 1 or less, characterized by an emission temperature, T_s, of about 5900 K (Fig. 2.2); the blackbody radiant intensity curve is modulated by the solar Fraunhofer lines in the visible wavelength region. In this band, the radiative spectral intensity of a 5900 K blackbody has a maximum at a wavelength, λ, in the blue at about $\lambda = 491$ nm. The total solar radiative emission per unit area, M, or exitance (see Chapter 8), is

$$M = \sigma_{SB} T_s^4 \qquad \mathrm{W\ m^{-2}} , \tag{2.1}$$

where the Stefan–Boltzmann constant is $\sigma_{SB} = 5.67 \times 10^{-8}$ W (m^2 K^4)$^{-1}$. At the earth's surface, at a radius of one astronomical unit ($R_{es} = 1.49598 \times 10^{11}$ m), the mean theoretical solar irradiance, $\langle S_{th} \rangle$, is, according to the numbers above, $\sigma_{SB} T_s^4 (R_s/R_{es})^2 = 1.487$ kW m^{-2}, where R_s is the radius of the sun ($R_s = 6.960 \times 10^8$ m). The correct value at the top of the atmosphere, i.e., the solar "constant" is, from observation,

$$\langle S \rangle = 1.376 \ \mathrm{kW\ m^{-2}} , \tag{2.2}$$

which is somewhat lower than the theoretical value because of the graybodiness of the sun. In addition, this *insolation* is not constant but varies by $\pm 3.2\%$ annually because of the ellipticity of the earth's orbit. The projection of the disk of the earth in the sun's direction receives an amount of solar power, P_s, of

$$P_s = \pi R_e^2 \langle S \rangle , \tag{2.3}$$

of which a fraction, $\langle \alpha \rangle$, the mean *albedo* or reflected power, is reflected back to space, chiefly by clouds, snow, ice, and desert surface. Since the total area of the earth's surface is $4\pi R_e^2$, the average power flux absorbed per unit area is

$$\tfrac{1}{4} \langle S \rangle (1 - \langle \alpha \rangle) = 240.8 \ \mathrm{W\ m^{-2}} . \tag{2.4}$$

It is this energy that is responsible for the mean temperature of the earth, and since the planet is neither heating up nor cooling down (at least not on decadal or shorter time scales), the same amount of energy must be re-radiated to space as infrared radiation. If the earth, too, were a blackbody, its equilibrium emission temperature, T_e, would be found from the equation: reradiation = insolation. Thus

$$4\pi R_e^2 \sigma_{SB} T_e^4 = \pi R_e^2 (1 - \langle \alpha \rangle) \sigma_{SB} T_s^4 (R_s/R_{es})^2 . \tag{2.5}$$

For an average albedo, $\langle \alpha \rangle = 0.3$, as measured from spacecraft, Eq. 2.5 yields a theoretical value for T_e of 260 K. However, the re-absorption of emitted infrared energy by radiatively active constituents in the atmosphere (the greenhouse effect), coupled with convection, raises the observed value for T_e to about 288 K. Figure 2.2 shows the spectral exitance of a 300 K blackbody as an envelope for the observed IR emission from the earth. By the Wien displacement law, the wavelength, λ_m, of the maximum of the Planck distribution of blackbody radiation at temperature T is

$$\lambda_m = \frac{\alpha_r}{T} , \tag{2.6}$$

where $\alpha_r = 2897.8\ \mu\text{m K}$. For the earth at $T_e = 288$ K, the maximum occurs at

$$\lambda_m = 10.1\ \mu\text{m} . \tag{2.7}$$

This region of infrared emission is termed the *thermal infrared,* and it is coincidently a region of relatively high transparency of the atmosphere (see Fig. 2.2). One would then expect that the land and water would have a globally and seasonally averaged equilibrium temperature, in degrees Celsius, of

$$T_{eq} = T_e - 273.15 \simeq 15°\text{C} . \tag{2.8}$$

This temperature is not far from the observed average surface temperature of the oceans, which have extreme values of approximately $-2°$C to $+35°$C and which have by far the largest heat capacity of the earth's surface. Thus the processes of insolation, reflection, absorption, and re-radiation establish the gross temperature balance of the earth.

Figure 2.3 is a schematic diagram of the flow of energy in the geophysical system consisting of atmosphere, hydrosphere (ocean, lakes, and other waters), lithosphere (land), and cryosphere (ice). Of the totality of incoming radiation, 30% is reflected by clouds, dust, and the earth's surface (the albedo); 70% is re-radiated as IR radiation, which in turn is divided into 64% emitted by the radiatively active gases and clouds in the atmosphere, and 6% by the earth's surface, both land and water. Before this re-emission occurs, many transmutations of the incident energy have taken place, as the diagram suggests, with 20% of the total incident radiation being directly absorbed by the atmosphere, and 50% entering the nonatmospheric portions of the system – mainly the oceans, where it heats the upper levels of the sea and directly contributes to the oceanic *thermohaline circulation* (temperature- and salt-driven). As will be seen below, it also indirectly contributes to the wind-driven circulation via evaporation of water in the tropics and subtropics. Water has an enormous specific heat, the second highest of any

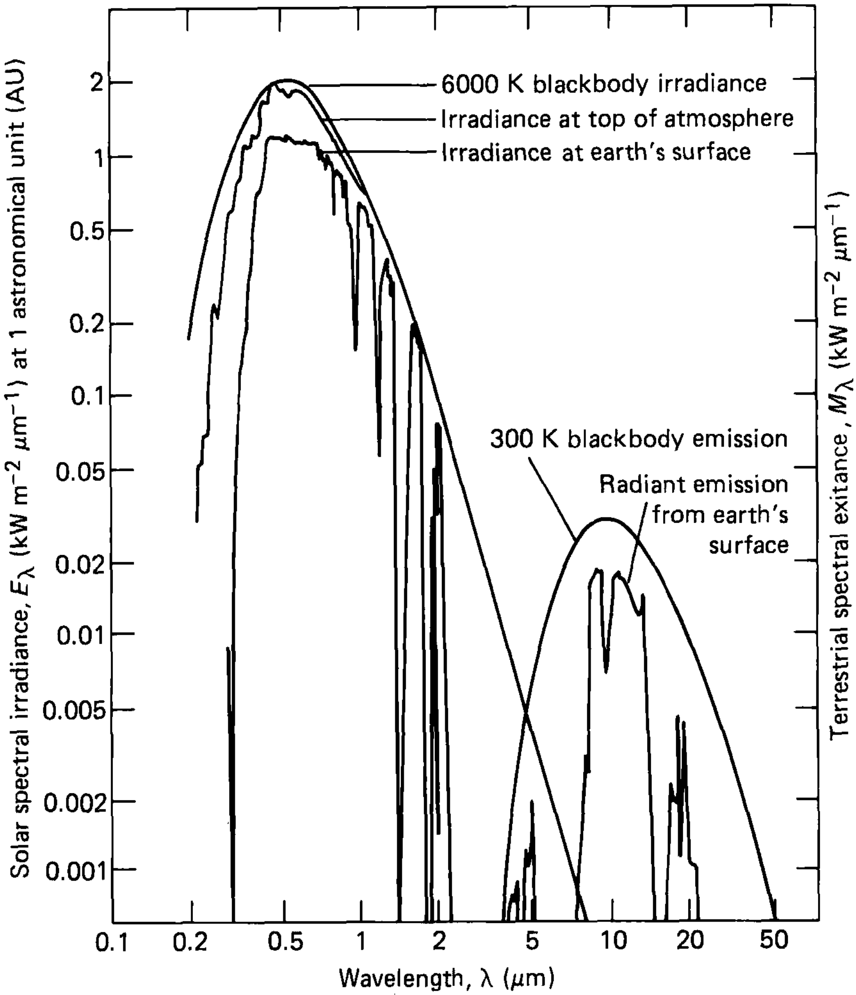

Fig. 2.2 Incident solar spectral irradiances at top of atmosphere and at the earth's surface, compared with that from a 6000 K blackbody (left). Spectral emittance from the earth's surface, compared with that from a 300 K blackbody (right). [Adapted from Smith, D. G., Ed., *The Cambridge Encyclopedia of Earth Sciences* (1981).]

known substance; for seawater, the specific heat at constant pressure, C_p, is 0.955 cal (g °C)$^{-1}$, or 3998 J (kg °C)$^{-1}$ at a temperature, T, of 20°C, a surface pressure, p, of 1.024×10^5 Pa, and a salinity, s, of 35 practical salinity units (psu, or 35 parts per thousand). It also has a very large *latent heat of vaporization, L_v*: