DESCRIPTIVE PHYSICAL OCEANOGRAPHY

3rd (SI) Edition

G L Pickard

Descriptive Physical Oceanography

AN INTRODUCTION

by

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Preface to the Third Edition

THE DEVELOPMENT of interest in oceanography in recent years has led to an increased demand from students for information on the subject. The texts available hitherto have been either more elementary in treatment or more comprehensive and extensive than may be desirable for an introduction to the subject for the undergraduate. The present text is an attempt to supply information on the Synoptic or Descriptive aspects of Physical Oceanography at a level suitable as an introduction for graduate students, for undergraduates in the sciences and possibly for senior school students who wish to learn something of the aims and achievements of this field of scientific study.

In preparing this third edition, the endeavour has been to bring up-to-date the presentations of the topics covered in the earlier editions and to add brief descriptions of some new features, such as ocean eddies, without substantially increasing the length of the text. One other change which has been made is in the units used. Until recently, physical oceanographers used a mixed system of metric units, with some from other systems, which grew up with the development of the field and to suit particular aspects of it. However, the uniform International System of Units (SI units) is now coming into general use both in science and in everyday life and, although the oceanographic fraternity has not yet formally agreed to convert to this system, it is being required by many journals and the decision was made to introduce SI units in this edition to conform to the general trend (and for consistency with *Introductory Dynamic Oceanography* by Pond and Pickard). For convenience, an Appendix has been added describing the units used in descriptive oceanography and their relations to the earlier mixed system of units.

In presenting the synoptic approach it must be emphasized that this represents only one aspect of physical oceanography. The other, and complementary one, is the dynamical approach through the laws of mechanics. This is described in other texts such as those by McLellan, Pond and Pickard, Sverdrup *et al.* or Von Arx listed at the end of this volume. The student who requires a full introduction to physical oceanography must study both aspects.

The text is intended to be introductory to the subject. For the student in physics and mathematics it should serve to present to him the main aspects of the field before he proceeds to the more advanced texts and original literature making free use of mathematical methods. For the student in the biological sciences it may supply sufficient information on descriptive physical oceanography to provide the necessary background for his studies of the fauna and flora of the sea. The text by Tchernia provides a more detailed coverage of the oceans by regions.

If the reader concludes the text with a feeling that our knowledge of the sea is incomplete at present, one of the author's objectives will have been achieved. This was to indicate to the student that there is still much to be learned of the ocean and that if he is interested in observing the marine world and interpreting it there are still many opportunities for him to do so.

For the student who wishes to extend his study of physical oceanography suggestions for further reading are given at the end of this book. These suggestions are chiefly to textbooks which enlarge on many aspects described in the present one and contain references to the original literature for those who have access to it.

The text is based on a course presented by the author and colleagues for twenty-five years at the University of British Columbia to introduce undergraduate and graduate students to synoptic oceanography. It owes much to the more comprehensive text *The Oceans*, by Sverdrup, Johnson and Fleming, and the author wishes to acknowledge this and also the stimulation received during a year at the Scripps Institution of Oceanography. The author is particularly indebted to Dr. J. P. Tully of the Pacific Oceanographic

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Group for initiating him into oceanography and for encouragement since, and to Dr. R. W. Burling and others for reading the original manuscript and offering constructive comments on that and on the two previous editions of the text. Finally, it will be realized that although the author has personal experience of some aspects of physical oceanography and of some regions, he has relied largely on the results and interpretations of others in order to present an adequate coverage of the subject. He therefore gratefully acknowledges his indebtedness to the many oceanographers whose works he has consulted in texts and journals in assembling the material for this book.

G.L.P.

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CHAPTER ONE

Introduction

OCEANOGRAPHY is the general name given to the scientific study of the oceans, with an emphasis on their character as an environment. It is conveniently divided in terms of the basic sciences into physical oceanography, biological oceanography, chemical oceanography and geological oceanography. This book is concerned primarily with one aspect of the first of these.

The basic goal of oceanographic study is to obtain a clear and systematic description of the oceans, sufficiently quantitative to permit us to predict their behaviour in the future with some certainty. While we can do this in a general fashion for some characteristics and in some regions, we are a long way from being able to predict details with confidence. In other words, there is still a great deal of scientific study of the oceans to be done and understanding to be achieved.

Generally the individual scientist studying the ocean devotes himself to investigations in one of the sciences, but very often supporting information may be obtained from observations in other sciences. In fact, one of the intriguing aspects of oceanography is that it is not yet too highly compartmented or specialized, and there is much co-operation between those working in the different sciences.

There are many reasons for developing our knowledge of the oceans. As sources of food, of chemicals and of power, they are as yet only exploited to a very minor degree. They are still a vitally important avenue of transportation and are always likely to be. They form a sink into which industrial waste is dumped, but they do not form a bottomless pit into which material like radioactive waste can be thrown without due thought being given to where it may be carried by currents. The vast heat capacity of the oceans exerts a significant effect on the climate of the land, while the continuous movement of the currents and waves along the coast must be taken into account when piers, breakwaters and other structures are built.

In all these applications, and in many others, a knowledge of the circulation of the oceans is needed. The goal of the physical oceanographer is to obtain a systematic quantitative description of the character of the ocean waters and of their movements. The latter include the major ocean currents which circulate continuously but with fluctuating velocity, they include the variable coastal currents, the reversing tidal currents, the rise and fall of the tide and the waves generated by wind or earthquake. The character of the ocean waters includes those aspects, such as temperature and salt content, which determine density and hence vertical movement, and also includes dissolved substances or biological species in so far as they yield information about the currents.

The physical study of the ocean is approached in two ways. In what is called the synoptic or descriptive approach observations are made of specific features and these are reduced to as simple a statement as possible of the features themselves and of their relations to other features. The dynamical or theoretical approach is to apply the already known laws of physics to the ocean, regarding it as a body acted upon by forces, and to endeavour to solve the resulting mathematical equations to obtain information on the motions to be expected from the forces acting. In practice there are limitations and difficulties associated with both methods, and our present knowledge of the oceans has been developed by a combination of the synoptic and the dynamical approaches. The method is as follows. Preliminary observations give one some idea what features of the ocean require explanation. The basic physical law which is considered to apply to the situation is then used to set up an equation between the forces acting and the motions observed. A solution of this equation, even an approximate one, will give some idea of how the motions may vary in time or space. It may also suggest further observations which may be made to test whether the law selected or the features entered into the equation are adequate or not. If not, the theory is modified in the light of the test observations and the procedure of alternate observation of nature and development of the theory is pursued until a satisfactory theory is obtained. The method is typical of scientific research.

Our present knowledge in physical oceanography represents an accumulation of data, most of which have been gathered during the past hundred years. The purpose of this book is to summarize some of these data to give an idea of what we now know about the distribution of the physical characteristics of the ocean waters and of their circulation. The achievements of the alternate but parallel approach through the laws of mechanics are described in other texts such as those by McLellan, Pond and Pickard or Von Arx.

During its history physical oceanography has gone through several phases. Presumably ever since man started to sail the oceans he has been concerned with ocean currents as they affect the course of his ship. This distinctly practical approach is more a branch of the related field of hydrography, which includes the preparation of navigation charts and of current and tide tables, than of oceanography, but out of it came the study of the currents for the purpose of determining *why* they behave in the way they do as well as *how*. Many of the earlier navigators, such as Cook and Vancouver, made valuable scientific observations during their voyages in the late 1700's, but it is generally considered that Mathew Fontaine Maury in about 1860 started the systematic large scale collection of ocean current data, using ship's navigation logs as his source of information. Many physical data on surface currents and winds were collected, and still are, from this source. The first major expedition designed expressly to study all the scientific aspects of the oceans was that of H.M.S. *Challenger* which circumnavigated the globe from 1872 to 1876. The first large scale expedition organized primarily to gather physical oceanographic data was the German *Meteor* expedition to study the Atlantic Ocean from 1925 to 1927. Expeditions in increasing numbers in the following years have added to our knowledge of the oceans, both in single ship and in multi-ship operations including the loosely co-ordinated worldwide International Geophysical Year projects in 1957–58, the International Indian Ocean Expedition in 1962–65, the oceanographic aspects of GATE in 1974 (GARP Atlantic Tropical Experiment where GARP = Global Atmospheric Research Programme) and, in the late 1970s, POLYGON, MODE AND POLYMODE in the Atlantic (see Chapter 7), the Coastal Upwelling Ecosystems projects in the Pacific and Atlantic, the continuing NORPAX (North Pacific Experiment) and ISOS (International Southern Ocean Study) and many other projects. Nevertheless, there are still areas such as the Arctic, the Southern Ocean and the southern Pacific and Indian Oceans for which we have very limited information.

Some of the earliest theoretical studies of the sea were of the surface tides by Newton (1687) and Laplace (1775), and of waves by Gerstner (1802) and Stokes (1874). Following this, about 1896, some of the Scandinavian meteorologists started to turn their attention to the ocean, since dynamical meteorology and dynamical oceanography have much in common. The present basis for dynamical oceanography owes much to the early work of Bjerknes, Helland-Hansen, Ekman and others.

In recent years attention has been given to other phases, including the circulation and water properties at the ocean boundaries along the coasts and in estuaries, and also in the deep and bottom waters of the oceans. The coastal waters are more accessible for observation than the open ocean but show much larger fluctuations in space and time, and also present more difficulties for theoretical study. The deep and bottom waters are very difficult to observe: this makes it hard to acquire information to start the theoretical studies, and also to test them.

The plan followed in this book will be to describe briefly the ocean basins and something of their topography as it affects ocean circulation, and then to introduce some of the terminology of

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physical oceanography. After a brief summary of the properties of sea-water, a general description of the distribution of water characteristics, both in the vertical and in the horizontal, will be presented to give the reader some feeling for typical conditions. A discussion of the sources of gain or loss of heat and of water to the ocean follows, and then a description of instruments and of methods of data presentation. After this there is a description of the water characteristics and of the currents in the individual oceans of the world, and finally a few comments on the present state of our knowledge in descriptive physical oceanography.

Perhaps a comment upon the title of this book should be made before proceeding. Among oceanographers the term "synoptic oceanography" is understood to refer to the method of approach which starts with the observation of data and then continues with the preparation of a concise description, i.e. a "synopsis". But description and synopsis are only the start. The oceanographer then seeks regularities in the data and interprets the distributions of properties with the object of obtaining information on the circulation. Therefore a more exact title for this aspect would be "Interpretative Oceanography", but unfortunately this term is not in general use. "Synoptic Oceanography" was the first choice for a title and would be clear in its meaning to oceanographers. However, this book is not intended for trained oceanographers but for would-be oceanographers or for those who wish to introduce themselves to this aspect of science. In the end, the title "Descriptive Physical Oceanography" was chosen in the hope that this would best indicate the character of its contents to those who were not yet familiar with the field. It is hoped, however, that the reader who completes its study will no longer be a novice but will by then appreciate that "synoptic" oceanography does not stop at description but continues with its main aim, interpretation.

CHAPTER TWO

Ocean Dimensions, Shapes and Bottom Materials

THE OCEANS are basins in the surface of the solid earth containing salt water. The purpose of this chapter is to introduce some of the nomenclature and to direct attention to some features of the basins which have a close connection with the circulation and are of importance to the physical oceanographer. A more detailed description of the geology and geophysics of the ocean basins is given in *Submarine Geology* by Shepard or in the articles by Menard and by Bullard in *Oceanography* mentioned in the Suggestions for Further Reading at the end of this book.

In order to appreciate the shapes of the oceans and seas it is almost essential to examine them on a globe, since map projections on to flat paper always introduce distortions when large portions of the earth are to be represented. From the oceanographic point of view it is convenient to distinguish the various regions in terms of their oceanographic characteristics, particularly their circulations. Anticipating the information which will be given in later chapters, the major ocean areas will be defined now as the Southern Ocean, the Atlantic Ocean, the Pacific Ocean, the Indian Ocean, and the Arctic Sea. The last four are clearly divided from each other by land masses but the divisions between the Southern Ocean and the others to its north are determined only by the characteristics of the ocean waters and by their circulation as will be described in Chapter 7. Then there are smaller bodies of water such as the Mediterranean Sea, the Gulf of Mexico, the Bering Sea, etc., which are clearly bounded by land or by island chains. The term "sea" is also used for a portion of an ocean which is not divided off but has local distinguishing oceanographic characteristics. Examples are the Norwegian, the Labrador and the Tasman Seas.

Looking at a globe again, it is evident that more of the earth's surface is covered by sea than by land, about 71% compared to 29%. Furthermore, the proportion of water to land in the southern hemisphere is much greater (4:1) than in the northern hemisphere (1·5:1). In area, the Pacific Ocean is about as large as the Atlantic and the Indian Oceans combined. If one includes the neighbouring sectors of the Southern Ocean with the three main oceans north of it, then the Pacific Ocean occupies about 46% of the total world ocean area, the Atlantic Ocean about 23%, the Indian Ocean about 20%, and the rest combined about 11%.

The average depth of the oceans is close to 4000 metres while the seas are generally about 1200 metres deep or less. Relative to sea level the oceans are much deeper than the land is high. While only 11% of the land surface of the earth is more than 2000 metres above sea level, 84% of the sea bottom is more than 2000 metres deep. However, the maxima are more similar: the height of Mt. Everest is about 8840 metres while the maximum depth recorded in the oceans is 11,524 metres by H.M.S. *Cook* in the Mindanao Trench in the western Pacific.

Although the average depth of the oceans, 4 km, is a considerable distance, it is small compared to the horizontal dimensions of the oceans, which are of the order of 5000 to 15,000 km. An idea of the relative dimensions of the Pacific Ocean may be obtained by stating that they are much the same as a sheet of lightweight typing paper. This analogy makes the oceans appear as a very thin skin on the surface of the earth. Relative to the major dimensions of the earth they are thin, but there is a great deal of detail and structure in this thin layer between the surface and the bottom of the oceans.

Very often we wish to present some of these details by drawing a vertical cross-section of a part of the oceans. A drawing to true scale would have the relative dimensions of the edge of a sheet of paper and would either be too thin to show details or too long to be convenient. Therefore we usually have to distort our cross-section by making the vertical scale much larger than the horizontal one. For instance we might use a scale of 1 cm on the paper to represent 100 km horizontally in the sea while depths might be at a scale of 1 cm to represent 100 m, i.e. 0·1 km. In this case the vertical dimensions on our drawing would be magnified by 1000 times compared to the horizontal ones. This gives us room to show the detail we wish but exaggerates the slope of the sea bottom or of lines of constant property drawn on the cross-section. It is

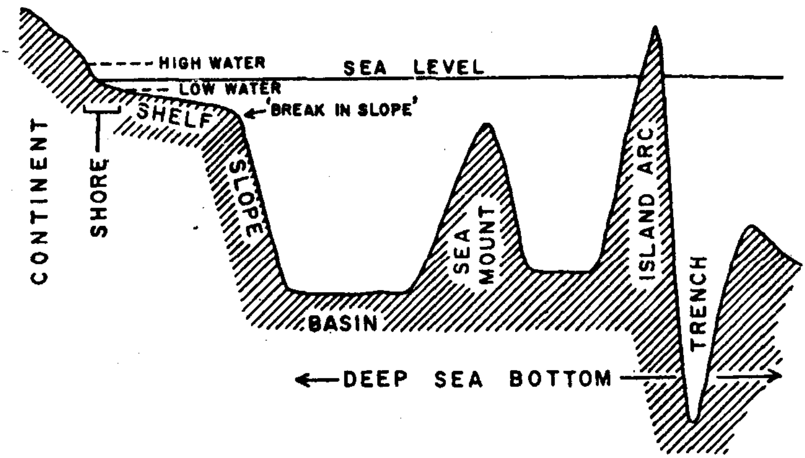

FIG. 1. *Section through ocean floor to show principal features schematically.*

as well to remind oneself occasionally that such slopes are in reality far less than they appear on the cross-section drawings. For instance, a line of constant temperature with a real slope of 1 in 100 would be exceptionally steep in the ocean, one of 1 in 1000 very steep, and 1 in 10,000 more usual.

The continents form the major lateral boundaries to the oceans, and the detailed features of the shoreline and of the sea bottom are important in their effects on circulation. Starting from the land, the main divisions recognized are the shore, the continental shelf, the continental slope and the deep-sea bottom (shown schematically in Fig. 1).

The *shore* is defined here as that part of the land mass close to the sea which has been modified by the action of the sea. It is as well to note in this connection that there is ample evidence to indicate that sea level in the past has varied over a range of about 100 m when glaciers were smaller or larger than they are now. The beach is the seaward limit of the shore and extends roughly from the highest to the lowest tide levels. Sandy beaches are often in a state of dynamic equilibrium. That is to say, they may be composed of sand all the time but it may not always be the same sand. This may be continually moving along the shore under the influence of waves and nearshore currents. This state is very often made evident by the way in which sand accumulates against new structures built on the shore, or by the way in which it is removed from a beach when a breakwater is built in such a way as to cut off the supply of sand beyond it. On some beaches, the sand may be removed by currents associated with high waves at one season of the year and replaced by different currents associated with lower waves at another season.

The *continental shelf* extends seaward from the shore with an average gradient of 1 in 500. Its outer limit (the "break-in-slope") is set where the gradient increases to about 1 in 20 on the average to form the continental slope down to the deep-sea bottom. The shelf has an average width of 65 km. In places it is much narrower than this, while in others, as in the Bering Sea or the Arctic shelf off northern Siberia it is much wider. The bottom material is dominantly sand, with rock or mud being less common. The division between the shelf and the slope is made on the basis of the break-in-slope which is usually clearly evident when one examines a vertical cross-section of the sea bottom from the shore outward. The average depth at the break-in-slope is about 130 m. Most of the world's fisheries are located on the continental shelf.

The *continental slope* averages about 4000 m vertically from the shelf to the deep-sea bottom, but in places extends as much as 9000 m vertically in a relatively short horizontal distance. In general the continental slope is considerably steeper than the slopes from lowlands to highlands on land. The material of the slope is predominantly mud, with some rock outcrops. Very typical features of the shelf and slope are the submarine canyons which are of world-wide occurrence. They are valleys in the slope, either V-shaped or with vertical sides, and are usually found off coasts with rivers and never off desert areas.

The *deep-sea bottom* is the last and most extensive area. Depths of 3000 to 6000 m are found over 76% of the ocean basins, with 1% being deeper. Perhaps the most characteristic aspect of the deep-sea bottom is the variety of its topography. Before any significant deep ocean soundings were available the sea bottom was regarded as uniformly smooth. When detailed sounding started in connection with cable laying, it became clear that this was not the case and there was a swing to regarding the sea bottom as predominantly rugged. Neither view is exclusively correct, for we know now that there are mountains, valleys and plains on the ocean bottom just as on land. The characteristic features are, as on land, either basically long and narrow (welts and furrows) or of roughly equal lateral extent (swells and basins). The Mid-ocean Ridge is probably the most extensive single feature of the earth's topography. Starting south of Greenland it extends along the middle of the Atlantic from north to south and then through the Indian and Pacific Oceans. In the Atlantic it separates the bottom waters, as can be seen from their very different properties east and west of the ridge (Fig. 24). However there are narrow gaps in this ridge at some of the "fracture zones". These are roughly vertical planes perpendicular to the ridge and on either side of which the crust has moved in opposite directions perpendicular to the ridge. This leaves a gap in the ridge through which water below the ridge top may leak from one side to the other. One such is the Romanche Gap through the Mid-Atlantic Ridge close to the equator.

Individual mountains ("seamounts") are widely distributed in the oceans. Some project above the surface to form islands, while the tops of others are below the surface.

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