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S. A. Thorpe
Frontmatter
More information

The Turbulent Ocean

The subject of ocean turbulence is still in a state of discovery and development, with many intellectual challenges. This book provides a description of the principle dynamic processes that control the distribution of turbulence, its dissipation of kinetic energy and its effects on the dispersion of properties such as heat, salinity, and dissolved or suspended matter in the deep ocean, the shallow coastal and the continental shelf seas. Particular focus is given to the measurement of turbulence, and to the consequences of turbulent motion in the oceanic boundary layers at the sea surface and near the seabed, especially near sloping and rough topography, sea straits and fjords. The processes leading to turbulence and its generation by breaking internal waves are described in some detail and illustrated by examples taken from laboratory experiments and field observations. Because of its all-pervading nature, turbulence is at the heart of ocean science, and some appreciation of its effects is essential for those involved in research, not only in physical oceanography but in biological, chemical and geophysical aspects of ocean science.

The Turbulent Ocean provides an excellent resource for senior undergraduate and graduate courses, as well as an introduction and general overview for researchers. It will be of interest to all those involved in the study of fluid motion, in particular geophysical fluid mechanics, meteorology and the dynamics of lakes.

Steve Thorpe joined the staff of the National Institute of Oceanography, later the Institute of Oceanographic Sciences, in 1962, and became Professor of Oceanography at Southampton University in 1986. He has made experiments to study the nature of turbulence and internal waves in the laboratory, at sea and in lakes, and has been involved in the development of novel sensors, instruments and methods of observation. He was awarded the Walter Munk Award by the US Office of Naval Research and the Oceanography Society for his work on underwater acoustics. He is also proud to have been elected a Fellow of the Royal Society of London, to be awarded the Fridtjof Nansen medal of the European Geophysical Society in recognition of his fundamental experimental and theoretical contributions to the study of mixing and internal waves in the oceans, and the Society's Golden Badge for his introduction of a travel award scheme for young scientists. He is now an Emeritus Professor at the University of Southampton and an Honorary Professor at the School of Ocean Sciences, Bangor.

The Turbulent Ocean

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With love to Daph, my wife of 41 years,
for her great support and enduring toleration.

‘For I have learned to look on nature, . . .
. . . And I have felt
A presence that disturbs me with the joy
Of elevated thoughts, a sense sublime
Of something far more deeply interfused,
Whose dwelling is the light of setting suns,
And the round ocean and the living air,
And the blue sky, and in the mind of man.’

From ‘*Lines composed a few miles from Tintern Abbey*’
by William Wordsworth, 1798.

Contents

Preface

The idea of writing this book developed from the need for a text suitable in teaching a course on ocean physics to undergraduates and masters course students with some knowledge of physical processes, but not necessarily in fluids. The course demanded a text describing basic processes in fluids (many of which are beautifully illustrated in Van Dyke's (1982) book, a valuable introduction for students unfamiliar with fluid motion), and how these processes are manifest and why they are important in the ocean. In choosing as a title, *The Turbulent Ocean*, rather than *Ocean Turbulence*, I wish to convey an intention not to focus heavily on the complex and involved study of turbulence, but rather on the processes in the ocean leading to turbulence, its extraordinary and sometimes unexpected structure, and its multifaceted and profound effects in ocean dynamics.

This is therefore not intended to provide the sort of basic introduction to turbulence given, for example, in the excellent book by Tenneckes and Lumley (1972). Little is said of the general theory of turbulent motion or of the problems involved in its statistical sampling and in the treatment of data, particularly the problems encountered in producing and interpreting energy spectra even though these must be faced by those measuring turbulence in the ocean. Rather I describe and focus attention on the physical processes that lead to turbulence, and on its effects in the ocean.

I was encouraged by a reviewer of an early description of the book to choose a title including the word 'mixing', but this is only one aspect of the effect of turbulence and although arguably the most important, there are many others. There was also an expectation that 'modelling' would be a dominant subject in a text dealing with turbulence in the ocean. But to do justice to that subject would demand a further (and, for me and perhaps for some students too, a duller) book. The reader will find references to modelling, but not details.

I have deliberately included much that will be beyond the scope of many undergraduate and postgraduate courses, so that the text provides both an introduction and a review of present knowledge that may be of value to those beginning or already engaged in research. My aim is to provide a text that is broad but not comprehensive, a text of which parts can be selected and used according to the requirements of the reader, whether teacher, student or researcher. I do not present an account ready-made as a teaching course – the best courses reflect the interests, strengths and expertise of the teacher. Rather the text is intended to provide material from which many different courses might be taught by the selection of appropriate sections. I have tried to assemble some illustrations of processes that may be compared, critically, with one another. Readers wishing to discover more are directed in the footnotes and references to more extensive and, sometimes, more rigorous accounts of the subject matter. Unlike a conventional textbook that generally sticks strictly to proven (or currently accepted) facts, the text includes conjectures and speculations as well as established knowledge. This is inevitable because of the state the subject is in – knowledge is incomplete with even gross energy balances yet uncertain, if not unknown and unclosed, with a frequent lack of suitable oceanographic data against which to test hypotheses. In learning about a subject, it is moreover of value to discover both what is known and what is surmised. Whilst the former is often exciting, the latter (offering the opportunity to devise a better explanation) can be stimulating. I have tried to distinguish clearly between the facts and the speculation, but have included the latter 'in the hope of stimulating others to remedy the defect' (Phillips, 1966). Because the subject is of great importance, of current interest and considerable activity, it is inevitable that more will soon be discovered. Whilst some of the information presented here has already stood the test of time, much is yet uncertain and hopefully, before long, will be revised and improved by those unwilling to accept the unsatisfactory status quo.

I have drawn extensively in the early chapters on the findings and images of laboratory experiments to illustrate and quantify processes that occur in the ocean. These are examples of some of the rich and mutually beneficial interrelations between fluid mechanics and the study of the physics of the oceans (and lakes – for limnology too provides and gleans information from oceanography). Both fields – fluid dynamics and physical oceanography – have gained from the other, either through the stimulation to investigate new and far-reaching problems to which attention has been drawn through observations or by the explanation of previously unexplained processes active in the often very high Reynolds number flows of the natural environment, Reynolds numbers unattainable in the laboratory. It is common to find papers in physical oceanography supported by information coming from theoretical, laboratory or lake studies in fluid dynamics, and many papers in the fluid dynamics literature address problems first recognized in the context of oceanography. Addressing generic problems at the heart of fluid processes, these often go well beyond what is sometimes referred to as 'geophysical fluid dynamics'.

The control of fluid motion achievable in the laboratory experiments described in this book, from Reynolds' and Joule's onwards, is never obtainable in the ocean. In consequence observations made at sea are often affected by the presence of unforeseen or apparently irrelevant variations that prevent a clear definition or identification of processes. This, and the commendable desire to obtain an 'overall' description, for example of energetics, have sometimes led to a predominantly numerical approach to measurement and analysis that disregards the underlying patterns of motion that provide vital clues to causality. Sometimes the opportunity to describe mechanisms and 'structure' has been lost by the adoption of spectral approaches to data collection and analysis. 'Coherent structure' is a thread leading through the text. The patterns seen in turbulent flows (of which some are illustrated in the figures), sometimes detected by conditional sampling or pattern recognition through a veil of overlying variability, are fascinating and sometimes remarkably beautiful. How they come about is still much of a mystery, but they carry information about the causes and nature of turbulence that may be of value when representing turbulence by 'parametrization' in predictive models. Discovering more about these features and causative processes remains a major challenge in the science of oceanography.

Finally I must remark that those wishing to obtain an impression of the dynamics of large bodies of fluid such as the ocean, and who do not have the means to measure for themselves, can learn a great deal by observation or photography of the sea surface, carefully watching the movement of waves and foam, and by following the motions traced in the turbulent atmosphere by clouds or plumes of smoke. They should challenge conventional ideas, and seek quantification and explanation of even the smallest details, structures and patterns for which none is obvious, available or satisfactory. There is still much about ocean turbulence that is not understood, as the content of the book makes clear.

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Structure and résumé

I have tried to provide the reader with some information about the motivation for studying the ocean and of the excitement of being involved in discovery and innovative research. Where it seems appropriate, some account is given of the relevant theoretical studies and of related laboratory experiments. Observations made at sea are introduced at an early stage where this is possible without its being too contrived.

Reference is made (sometimes in footnotes) to the way in which the subject has evolved and to those scientists who have been most prominent in its development. Although there are dangers in being carried far into the seductive and alluring subject of historical research (a pursuit that can capture and absorb the time and energy of the researcher – and too much knowledge of what is already known may deter interest and suppress novel ideas, for which there is always scope), I hope the details I have provided may tempt the interested readers into discovering more of the background to oceanographic research and how it is done. What is achieved or achievable sometimes depends more on the attitudes and social habits of individual scientists than on the facilities available to them.

Chapter 1 is intended to provide an introduction to the subject, and contains some basic information that is used in later chapters. Some of the factors that are germane to ocean turbulence, heat, temperature, density and energy, oscillations and flow stability, fluxes and stress, are discussed. Scales and parameters are defined and dispersion of particles and solutes is briefly addressed. The chapter concludes with an account of the evolution of knowledge in the still unfinished study of mixing in the deep ocean and its energetics, a discussion that sets the scene for some of the later chapters, and to which further reference is made in the concluding chapter.

Chapter 2 is about internal waves. This is by no means comprehensive, nor is it intended to be. But internal waves are very important in producing turbulence in the ocean – their breaking is described in Chapter 5 – and its purpose is to provide a description of the properties and nature of internal waves in the ocean, sufficient for the reader to appreciate their dynamics and, in later chapters, to understand their very important part in mixing the ocean. No comparable chapter is devoted to surface waves simply because whilst there are many ways in which internal waves can promote mixing, those associated with surface waves are more limited (see Chapter 9).

Chapters 3 and 4 describe two ways in which turbulence is commonly generated, through shear and convection, respectively. The account is based largely on laboratory experiments, and deals with 'transitional processes', those that lead from a relatively quiescent flow to a turbulent one, and which need to be explained before the processes by which internal waves are known (or may be assumed) to break can be addressed in Chapter 5. Convection is most frequently connected to boundary processes, and the law of the wall is introduced in Chapter 4 in connection with Monin–Obukov scaling. Double diffusive convection is also introduced here.

Although many of the concepts and scales relating to ocean turbulence have already been discussed in Chapter 1, it is in Chapter 6 that the means available for its measurement are described. One of the most significant characteristics of the density-stratified ocean is its fine-structure. The causes of fine-structure and their relation to turbulence in mid-water, the region beyond the direct influence of the solid boundary of the seabed or the air–sea interface, are discussed in Chapter 7, together with the effects of turbulence on diffusion and dispersion in this region.

The following five chapters are linked in one way or another to the effects of the oceanic boundaries. The nature of turbulent flows in the benthic boundary layer of the deep ocean, beyond the influence of motions induced by surface waves, is explored in Chapter 8. Turbulence driven by waves at the upper boundary of the ocean, the air–sea interface, and through shear and convection in the underlying mixed layer where coherent structures are sometimes evident (if not properly understood), is reviewed in Chapter 9. Turbulence in the shallow seas, strongly affected by the presence of the seabed, by surface wave and tidal motions, and sometimes by biological organisms, the regions most sensitive to and degraded by anthropogenic effects, is the subject of Chapter 10. The nature of turbulence near sloping boundaries on beaches at the edge of the sea and, in deep water, over continental and seamount slopes, is described in Chapter 11, and that near more irregular topography, including headlands and canyons, and in straits, fjords and lakes, is discussed in Chapter 12.

Much of the earlier account of turbulent motion is directed to the processes, generally those at small scales, which lead directly to turbulent dissipation of kinetic energy. Chapter 13 describes larger-scale motions that bear many of the characteristics of turbulence, contain sometimes-persistent coherent structures and, in particular, lead to dispersion at scales affected by the Earth's rotation. The final chapter, Chapter 14, reviews some of the important aspects of ocean turbulence that are yet to be fully investigated or quantified, one of which is the still poorly quantified sources of energy required to support ocean mixing.

The Appendices list parameters, values of some units and measures, particularly of the (sometimes presently uncertain) levels of energy and energy flux, and acronyms.

The subject spans a broad field in which there are so many references that a book could be filled by the reference list alone if all were included. Sometimes only the most recent significant papers are listed, those that refer to earlier papers, so that interested readers can trace the development of ideas to their originators. In so doing it is appreciated that injustice has been done to those who have made substantial advances, and the author can only apologise, pleading economy of space. He also apologises for the number of references made to his own publications, the inadequate excuse being that these are often, to him, the most familiar, or those from which it has been possible to reproduce figures with least difficulty.

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