An Introduction to Ocean Turbulence

This textbook provides an introduction to turbulent motion occurring naturally in the ocean on scales ranging from millimetres to hundreds of kilometres. It describes how turbulence is created and varies from one part of the ocean to another, what its properties are (particularly those relating to energy flux and the dispersal of pollutants) and how it is measured. Examples are given of real data and the instruments that are commonly used to measure turbulence. Chapters describe turbulence in the mixed boundary layers at the sea surface and seabed, turbulent motion in the density-stratified water between, and the energy sources that support and sustain ocean mixing.

Little prior knowledge of physical oceanography is assumed and the book is written at an introductory level that avoids mathematical complexity. The text is supported by numerous figures illustrating the methods used to measure and analyse turbulence, and by more than 50 exercises, which are graded in difficulty, that will allow readers to expand and monitor their understanding and to develop analytical techniques. Detailed solutions to the exercises are available to instructors online at www.cambridge.org/9780521676809. Further reading lists give direction to additional information on the background and historical development of the subject, while suggestions for further study encourage readers to probe further into more advanced aspects.

An Introduction to Ocean Turbulence is intended for undergraduate courses in physical oceanography, but will also form a useful guide for graduate students and researchers interested in multidisciplinary aspects of how the ocean works, from the surface to the seabed and from the shoreline to the deep abyssal plains. It complements the graduate-level text *The Turbulent Ocean*, also written by Professor Thorpe (Cambridge University Press, 2005).

STEVE THORPE was a Senior Scholar at Trinity College, Cambridge, where he studied mathematics and fluid mechanics, his PhD being awarded in 1966. He then spent 20 years at the UK Institute of Oceanographic Sciences, before being appointed Professor of Oceanography at Southampton University in 1986. He has carried out laboratory experiments on internal waves and turbulent mixing, and has measured and developed instrumental and analytical methods for studying waves and mixing in lakes, as well as making seagoing studies of turbulence in the boundary layers of the deep ocean and shelf seas. Professor Thorpe was awarded the Walter Munk Award by the US Office of Naval Research and the Oceanography Society, for his work using underwater acoustics, The Fridtjof Nansen Medal of the European Geophysical Society, for his fundamental experimental and theoretical contributions to the study of mixing and internal waves, and the Society's Golden Badge for introducing a scheme to assist young scientists. He became a Fellow of the Royal Society in 1991 and is now an Emeritus Professor at the University of Southampton and an Honorary Professor at the School of Ocean Sciences, Bangor.

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Preface

My book entitled *The Turbulent Ocean* (referred to later as TTO) was written in 2003. It provides an account of much of the knowledge that there was then of the processes leading to turbulence in the ocean, but it was not written as a course that might be followed and used to introduce students to turbulent flow. Rather, it is a text useful for those beginning or already involved in research. It might form the basis of a number of advanced courses about ocean physics, teachers selecting material according to their needs or specialities.

I was asked to write a shorter book, an introductory course on turbulence in the ocean. Although believing that the best undergraduate and postgraduate courses are based and modelled on a teacher's own experience and enthusiasms, and that to follow a 'set text' may be less enjoyable for students, I became convinced that a simplified text, more directly usable in teaching students unfamiliar with fluid motion, might be of value. Turbulence is a subject of which at least a basic understanding is essential in engineering and in many of the natural sciences, but particularly for students of oceanography. Moreover, many students, whose main interests are not in oceanography and who will not later address their talents to the study of the ocean, find interest in the sea and are motivated by aspects of their studies that are related or have application to matters of public and international concern, for example those of pollution and climate change that are at present being addressed by ocean scientists. A study of turbulent motion set in an oceanographic context can be attractive, satisfying and stimulating.

The purpose of the present book is consequently to provide a text that might be used in constructing and teaching an introductory course to students with a variety of academic abilities but who know little of ocean physics or turbulence. Much of the content has developed from a second-year course on ocean physics given in the Department of Oceanography at Southampton University, UK, in some 16 hours of lectures over a period of 4 weeks, supplemented by problems and additional reading undertaken by the students, a course attended by students whose main interests were in mathematics, physics, geology, biological oceanography or, generally, in marine science.

As in *The Turbulent Ocean*, the intricacy of turbulence theory is omitted. I recall, when an undergraduate, being totally mystified, if not frightened, by introductory lectures on turbulent motion that dealt with the subject in a largely statistical and analytical way, giving little or no insight into the dynamical processes of how it works. Unless students have a relatively high degree of ability in mathematics, the theoretical background is better faced after the basic concepts and ideas underlying the processes relating to turbulent motion have been absorbed and understood, and perhaps even after students have some understanding of the methods used to observe and measure turbulence. Neither is the numerical modelling of turbulence discussed here. That is best introduced to students in a separate and probably more mathematically demanding course once the processes involved in turbulence are firmly understood.

Unlike the earlier text, the material is almost entirely (but not quite!) restricted to what is well established and known, but I have also tried to explain the present limits of knowledge. I have taken the opportunity to include information that has been published since TTO was written, and to draw attention to errors that have come to my attention (specifically in footnotes 6 and 13 of Chapter 1, and footnote 13 of Chapter 6). I should be glad to be informed of any further errors found by readers in either that or this book.

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Notes on the text

The symbol • denotes important points or summary statements.

There are six chapters with substantial cross-referencing between them. The first is intended as a general introduction, before means of quantifying and measuring turbulence are introduced in Chapter 2. Chapter 3 deals with the turbulent boundary layers near the sea surface and seabed. Chapter 4 describes the relatively weak and patchy turbulent motion that is found in the density-stratified water between these two boundary layers. Chapter 5 is about turbulent dispersion, whilst Chapter 6 is a discussion of the present (and rapidly developing) knowledge of the sources and rates of supply of turbulence energy required to support mixing in the deep ocean.

The **illustrations** are a very important supplement to the text. It is through pictures that information is carried most readily, and often in the most pleasurable form, to the mind and memory of a reader. 'Cartoons' (or sketches) conveying new ideas or concepts, photographs and data presented in graphical form are often an output of research, to which they provide a useful introduction or overview. The figure captions add substantial information that is not always included within the text.

Lists of **Suggested further reading** are provided at the end of each chapter. These are of literature that students might be expected to peruse, if not read in detail, in the course of their study of the contents of the chapter, e.g., to appreciate better the historical derivation of knowledge. Also listed are reference works that will provide information about basic fluid dynamics or ocean physics, should it be required.

Papers referred to under **Further study** are guides to encourage more extensive in-depth study of the material of the chapter, possibly leading to new research. In many cases another pathway into such further study is through the sources of figures referred to in the figure captions.

Problems are listed at the end of each chapter and are denoted at a point in the text where they might be attempted by [**Pm.n**], where **m** is a chapter number and **n** the problem number within the chapter. Each problem number in this list is followed by a letter that denotes the problem's degree of difficulty: E = easy, M = mild, D = difficult and F = fiendish. The problems allow students to re-discover for themselves some of the now-accepted relationships, and provide experience in calculation and problem solving. These problems are *essential* elements in developing the ideas introduced in the text, and provide much additional information. They should preferably be read (if not solved) as students or readers advance through the course. The solutions to the problems are not given in this book but password-protected solutions to the problems are available online at www.cambridge.org/9780521859486. Quantitatively correct solutions are less important than the concepts introduced by the problems.

Lists of abbreviations, useful values etc. are provided on pages xv–xx for easy reference, and a map showing locations of places to which reference is made in the text is included on page xxii.

Scientific papers and books mentioned in text are all listed in the **References**, together with the numbers of pages on which they are mentioned.

The **Index** provides an entry to subjects that students may wish to locate or pursue, including 'dimensional arguments'.

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Mrs Kate Davis has kindly helped in the preparation of figures and I am most grateful for her care and professional attention to detail. I am also grateful to Drs Larry Armi and Jim Moum for providing very helpful information about their teaching courses.

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I also much appreciate the friendly help provided by the staff of Cambridge University Press in the preparation of this book and their care in its publication.

Abbreviations

AABW	Antarctic Bottom Water
abl	atmospheric boundary layer
ADCP	acoustic Doppler current profiler
ALACE	Autonomous Lagrangian Circulation Explorer
AMP	Advanced Microstructure Profiler
AUV	autonomous underwater vehicle
bbl	benthic or bottom boundary layer
CTD	conductivity–temperature–depth probe
FLIP	Floating Instrument Platform
HAB	harmful algal bloom
HOME	Hawaiian Ocean Mixing Experiment
HRP	High Resolution Profiler
LES	large eddy simulation
lhs	left-hand side
MSP	Multi-Scale Profiler
PIV	particle image velocimetry
pd	potential difference
pdf	probability distribution function (or histogram)
rhs	right-hand side
rms	root mean square
RFZ	Romanche Fracture Zone
SOFAR	SOund Fixing And Ranging
STABLE	Sediment Transport And Boundary Layer Equipment
TTO	*The Turbulent Ocean* by S. A.Thorpe, Cambridge University Press, 2005
VACM	vector-averaging current meter

Standard parameters and symbols

(with the section and, where appropriate, equation in which they are introduced)

C	Cox number (Section 4.4.2; (4.7)–(4.8))
C_D	the drag coefficient on the seabed (Section 3.4.1). (C_{Da} is used in this text to denote the drag coefficient of the wind on the water surface, with subscript a – standing for air – to emphasize that its value is different from C_D; it is defined in Section 3.4.1.)
I	isotropy parameter (Section 2.3.5; (2.14))
K_H	eddy dispersion coefficient (Section 5.2.1; (5.5))
$K_{H\infty}$	eddy dispersion coefficient at times $>> T_L$ (Section 5.2.1; (5.6))
K_S	eddy diffusion coefficient of salinity (Section 2.2.2)
K_T	eddy diffusion coefficient of heat or eddy diffusivity of heat (Section 2.2.2; (2.5))
K_ρ	eddy diffusion coefficient of density (Section 2.2.2)
K_ν	eddy viscosity (Section 2.2.1; (2.2))
L_L	Lagrangian integral length scale (Section 5.2.1; (5.3))
L_{MO}	Monin–Obukov length scale (Section 3.4.1; (3.6)–(3.7))
L_O	Ozmidov length scale (Section 4.4.1; (4.4))
L_{Ro}	Rossby radius (of deformation) (Section 1.8.2)
l_K	Kolmogorov length scale (Section 2.3.4)
N	buoyancy frequency (Section 1.7.2; (1.5))
Ra	Rayleigh number (Section 3.2.1, footnote 4)
Re	Reynolds number (Section 1.2; (1.1))
R_f	flux Richardson number (Section 4.4.2; (4.11))
Ri	gradient Richardson number (Section 4.2; (4.1))
Ri_B	bulk Richardson number (Section 4.5)
R_ρ	density gradient ratio (Section 4.8; (4.16))

T_L	Lagrangian integral time scale (Section 5.2.1; (5.2))
Γ	efficiency factor (Section 4.4.2; (4.9))
ε	rate of dissipation of turbulence kinetic energy per unit mass (Section 2.3.1; (2.9–(2.11))
σ_T	sigma-T (temperature) (Section 1.7.1)
σ_θ	sigma-theta (potential temperature) (Section 1.7.1, footnote 15)
χ_S	rate of loss of salinity variance (Section 2.3.3)
χ_T	rate of loss of temperature variance (Section 2.3.3; (2.12)–(2.13))

Units and their symbols

Unit	SI symbol (name)	kg–m–s equivalent
Force	N (Newton)	kg m s^{-2}
Pressure (force per unit area)	Pa (Pascal, 1 Pa = 10^{-5} bar)	kg m^{-1} s^{-2}
Energy	J (Joule)	kg m^2 s^{-2}
Power, energy flux	W (Watt, 1W = 1 J s^{-1})	kg m^2 s^{-3}
Energy dissipation rate per unit mass	W kg^{-1}	m^2 s^{-3}
Volume flux	Sv (Sverdrup)	10^6 m^3 s^{-1}

SI prefixes

Symbol	Name	Factor
E	exa	10^{18}
P	peta	10^{15}
T	tera	10^{12}
G	giga	10^{9}
M	mega	10^{6}
k	kilo	10^{3}
d	deci	10^{-1}
m	milli	10^{-3}
μ	micro	10^{-6}
n	nano	10^{-9}
p	pico	10^{-12}
f	femto	10^{-15}

Approximate values of commonly used measures

Radius of a sphere with the same volume as the Earth $= 6371$ km
Rotation rate of the Earth, $\Omega = 7.292 \times 10^{-5}$ s^{-1}
Mean depth of the ocean $= 3.795$ km
Area of the ocean surface $= 3.61 \times 10^{14}$ m^2
Mean area of sea ice $\approx 1.7 \times 10^{13}$ m^2 in March and 2.8×10^{13} m^2 in September
Volume of the ocean $= 1.37 \times 10^{18}$ m^3
Mass of the atmosphere $= 5.3 \times 10^{18}$ kg
Mass of the ocean $= 1.4 \times 10^{21}$ kg
Mass of water in lakes and rivers $\approx 5 \times 10^{17}$ kg
Speed of sound ≈ 1500 m s^{-1}
von Kármán's constant, $k = 0.40$–0.41
1 knot $= 0.5148$ m s^{-1}

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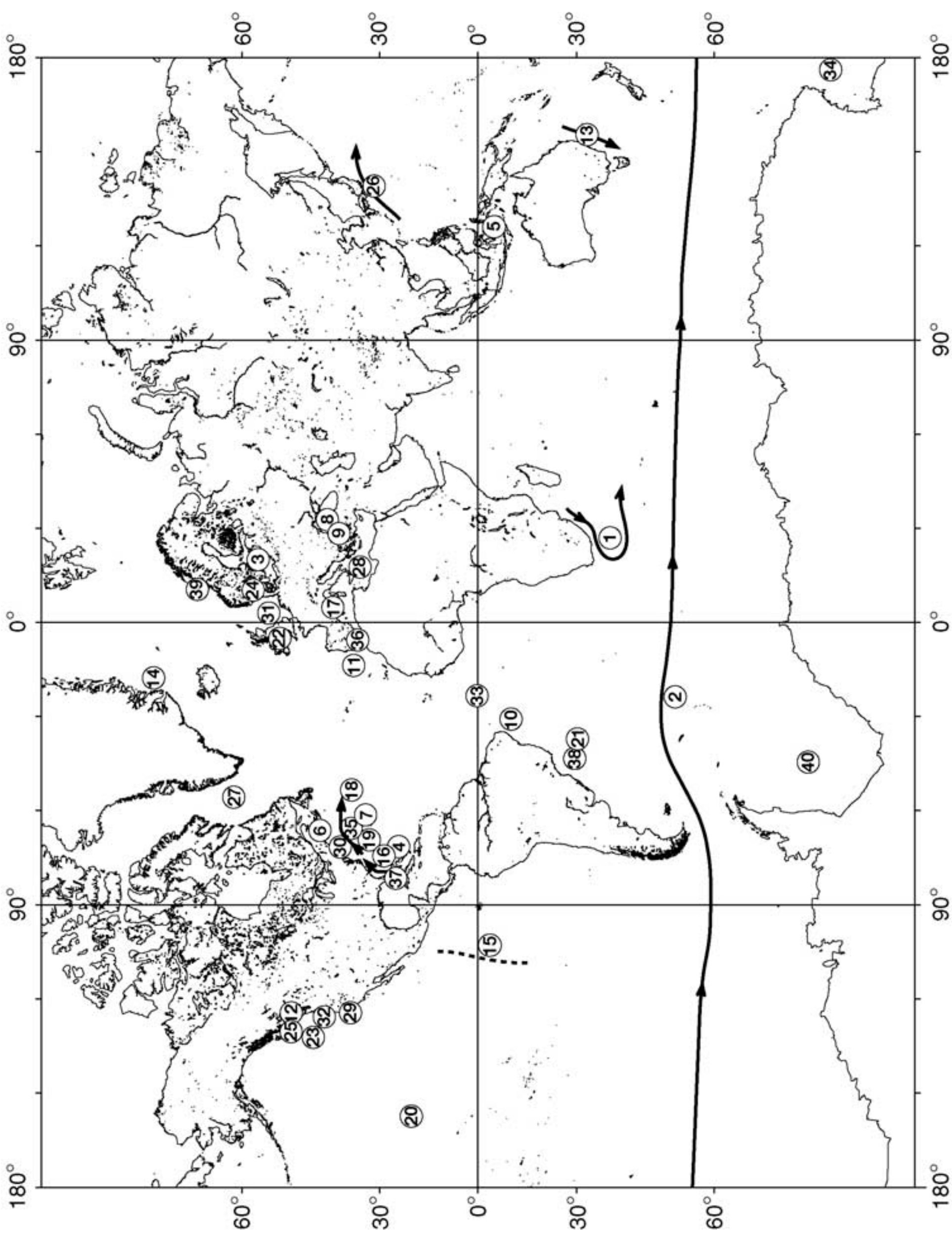

The general positions of some of the locations and currents referred to in the text.

1. Agulhas Retroflection Zone
2. Antarctic Circumpolar Current
3. Baltic Sea
4. Bahamas
5. Banda Sea
6. Bay of Fundy
7. Bermuda
8. Black Sea
9. Bosphorus
10. Brazil Basin
11. Discovery Gap
12. Discovery Passage
13. East Australia Current
14. East Greenland Sea
15. East Pacific Rise
16. Florida Current
17. Gulf of Lions
18. Gulf Stream
19. Hatteras Abyssal Plain
20. Hawaiian Ridge
21. Hunter Channel
22. Irish Sea
23. Juan de Fuca Ridge
24. The Kattegat
25. Knight Inlet, British Columbia
26. Kuroshio
27. Labrador Sea
28. Mediterranean Sea
29. Monterey Bay, California
30. New England Continental Shelf
31. North Sea
32. Oregon Continental Shelf
33. Romanche Fracture Zone (RFZ)
34. Ross Sea
35. Sargasso Sea
36. Strait of Gibraltar
37. Straits of Florida
38. Vema Channel
39. Vring Plateau
40. Weddell Sea