Cambridge University Press
978-0-521-87762-6 - Introduction to the Physical and Biological Oceanography of Shelf Seas
John H. Simpson and Jonathan Sharples
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Introduction to the Physical and Biological Oceanography of Shelf Seas

In this exciting and innovative textbook, two leading oceanographers bring together the fundamental physics and biology of the coastal ocean in a quantitative but accessible way for undergraduate and graduate students. Shelf sea processes are comprehensively explained from first principles using an integrated approach to oceanography – helping to build a clear understanding of how shelf sea physics underpins key biological processes in these environmentally sensitive and economically important regions. Using many observational and model examples, worked problems, and software tools, they explain the range of physical controls on primary biological production and shelf sea ecosystems.

Key features

- Opens with background chapters on the fundamentals of biology and physics needed to provide all students with a common, base-level understanding
- Develops the physical theory of each particular process in parallel with numerous data examples that describe the real-world impacts of physics on shelf sea biology
- Illustrates the success and failure of different model approaches to demonstrate their value as investigative research tools
- Boxes present extra detail and alternative explanations demonstrating the broader relevance of each topic
- Highlighted asides and anecdotes bring the reality and human aspects of ocean research work to life
- Physics sections include a set of non-mathematical summary points to help readers develop a qualitative understanding of the underlying processes
- Chapters end with summaries recapping key points to aid exam revision and problem sets that enable students to test their understanding

"This comprehensive and up-to-date book will be an ideal resource for both undergraduate and postgraduate students in pursuit of an all-round appreciation and understanding of the shelf seas. It really bridges a gap in the literature and the authors themselves pioneered much of the multidisciplinary research that has revealed a delicate interplay between the physical environment and life in the shelf seas."
Dr Robert Marsh *(University of Southampton)*

"Simpson and Sharples have combined courses in coastal physical dynamics and coastal biological oceanography to produce a textbook that is much greater than the sum of the individual disciplinary parts. Students and scientists alike will find the

discussions of sampling gear and deployment techniques an unusual and particularly useful aspect of this book. The authors are leaders in the study of the physics and biology of shelf seas and their experience and expertise are abundantly clear."
Professor Peter J.S. Franks *(Scripps Institution of Oceanography)*

"This text is a straightforward one-stop shop for students and professionals with a biological background who want to understand the basics of physical oceanography. It is very interesting and readable, and a great introduction the theoretical background a biologist needs to understand the large-scale physical dynamics of the world their organisms are inhabiting."
Professor Katherine Richardson *(Copenhagen University)*

"This book will prove to be a masterpiece with enduring value and fills a significant gap in physical oceanography textbooks by focusing on shallow seas. It reads well, is accessible to the intelligent, scientifically trained-non specialist and provides a solid foundation by which ecologists can learn much about the physical control of many ecological processes on shelf seas."
Distinguished Professor Malcolm Bowman *(State University of New York at Stony Brook)*

John Simpson leads a research group in the School of Ocean Sciences at Bangor University in Wales, which is developing new methods to observe and model turbulence and the mixing that plays a crucial role in biological production. He is a seagoing physical oceanographer with a broad interest in shelf seas and estuaries, and his research has focused on the physical mechanisms which control the environment of the shelf seas. He has taught Physics of the Ocean at Bangor and other universities worldwide for more than 40 years and was responsible for establishing the first Masters-level course in Physical Oceanography within the UK. In 2008, Professor Simpson was awarded the Fridtjof Nansen Medal of the European Geosciences Union for his outstanding contribution to understanding the physical processes of the shelf seas, and the Challenger Medal of the Challenger Society for his exceptional contribution to Marine Science.

Jonathan Sharples holds a joint chair at the University of Liverpool and the UK Natural Environment Research Council's National Oceanography Centre, and has taught courses in coastal and shelf oceanography at the universities of Southampton and Liverpool. He is an oceanographer whose research concentrates on the interface between shelf sea physics and biology. His work is primarily based upon observational studies at sea, combined with development of simple numerical models of coupled physics and biology. Professor Sharples has extensive seagoing experience off the NW European shelf and off New Zealand, having led several major interdisciplinary research cruises. His research has pioneered the use of fundamental measurements of turbulence in understanding limits to phytoplankton growth and controls on phytoplankton communities.

Introduction to the Physical and Biological Oceanography of Shelf Seas

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Additional resources for this publication at www.cambridge.org/shelfseas.

It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience.

Albert Einstein, 1933

I try not to think with my gut. If I'm serious about understanding the world, thinking with anything besides my brain, as tempting as that might be, is likely to get me into trouble.

Carl Sagan, 1995

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PREFACE

The seas of the continental shelf where the depth is less than a few hundred metres experience a physical regime which is distinct from that of the abyssal ocean where depths are measured in kilometres. While the shelf seas make up only about 7% by area of the world ocean, they have a disproportionate importance, both for the functioning of the global ocean system and for the social and economic value which we derive from them. Approximately 40% of the human population lives within 100 km of the sea, and the coastal zones of the continents are host to much of our industrial activity. Biologically, the shelf seas are much more productive than the deep ocean; phytoplankton production is typically 3–5 times that of the open ocean, and globally, shelf seas provide more than 90% of the fish we eat. They also supply us with many other benefits ranging from aggregates for building to energy sources in the form of hydrocarbons and we use our coastal seas extensively for recreation and transport. The high biological production of the shelf seas also means that these areas are important sources of fixed carbon which may be carried to the shelf edge and form a significant component of the drawdown of atmospheric CO_2 into the deep ocean.

Understanding of the processes operating in shelf seas and their role in the global ocean has advanced rapidly in the last few decades. In particular, the principal processes involved in the workings of the physical system have been elucidated, and this new knowledge has been used to show how many features of shelf sea biological systems are underpinned and even controlled by physical processes. It is the aim of this book to present the essentials of current understanding in this interdisciplinary area and to explain to students from a variety of scientific backgrounds the ways in which the physics and biology relate in the shelf seas. Our motivation to write such a book came from our extensive experience of teaching undergraduate and post-graduate courses in physical oceanography and biological oceanography to students from diverse disciplinary backgrounds and the realisation that there was an unfulfilled need for a textbook to present the maturing subject of shelf sea oceanography combining the physical and biological aspects.

As far as possible, we have endeavoured to give the book an interdisciplinary structure and to make it accessible to a wide range of students from different disciplinary backgrounds. Some of the early chapters deal separately with the fundamental principles of physics and biology necessary to understand the later material. The later chapters are arranged along interdisciplinary lines to illustrate the impact of physical processes on the biological response from primary production up to higher trophic levels. A full understanding of the physics inevitably requires some use of mathematical notation and we have included this for students from physical science disciplines. At the same time, we have provided summaries of the 'essential physics' which allow shortcuts through the mathematical development and should help students coming from biological backgrounds with limited experience of physics and mathematics to grasp the key physical ideas and appreciate how they affect the biology. Understanding of new concepts and their application is facilitated by supporting material in the form of problem sets and numerical exercises, within the book text and also hosted on the book website at Cambridge University Press. The book should form a suitable course text for advanced undergraduate and post-graduate oceanography students, but we anticipate that it will also be appropriate to courses introducing physical and biological science students to oceanography.

Both of us are seagoing oceanographers who have studied diverse shelf sea systems in different parts of the world. Much of our understanding and insight into the way the shelf seas work, however, has come from extensive observational work during national and international campaigns in the tidally energetic shelf seas of north-western Europe. Where possible we have used results from other shelf sea systems to illustrate parallels and differences between shelf sea systems but, inevitably, many of the examples we use are drawn from the European shelf which is now arguably the most intensively studied of all shelf systems in the global ocean. In this respect, we have not sought to produce a definitive volume on everything in shelf sea physical and biological oceanography. Rather, we have aimed to write a book that contains what we have found to be the key components of shelf sea physics and the way in which that physics impacts the biology in the European and other shelf sea systems. In doing so we have made extensive use of a variety of models, ranging from basic analytical constructs through to 1D turbulence closure models of vertical exchange to test simple and compound hypotheses about how the system works. By contrast, we have made rather little reference to large-scale 3D models which, while they are vital in applying understanding to the task of properly managing the shelf seas, have not yet contributed greatly to fundamental understanding of shelf sea processes.

Although shelf sea science has advanced rapidly in recent years, there are still many open questions about the processes involved, especially at the interfaces between physics, biochemistry and ecology. While a textbook is conventionally about established facts and well-supported theory, we have included some elements of conjecture and speculation in relation to the more interesting questions that remain, in the hope that they will stimulate further study and further refine our understanding of the shelf sea systems.

ACKNOWLEDGEMENTS

We would like to record our gratitude to the many individuals who have provided inspiration, advice and practical help in the preparation of this book. In particular we owe a debt to those (Joe Hatton, Ken Bowden) who inspired our interest in physics and physical processes in the ocean, and to those (Paul Tett, Patrick Holligan, Robin Pingree) who steered us towards interdisciplinary studies in shelf seas and whose work has helped to motivate us to write the book. Captain John Sharples and Eileen Ansbro Sharples had the courage to take their two kids on extended voyages aboard UK merchant vessels, which doubtless influenced the career path of one of us. Both of us have benefited greatly over the years from interacting with many able research students, too numerous to list, who have challenged our ideas and helped to refine them.

In the process of writing the book, we have received generous help and advice from many individuals, including Dave Bowers, Malcolm Bowman, Peter Franks, Mattias Green, Anna Hickman, Claire Mahaffey, Bob Marsh, Mark Moore, Kath Richardson, Tom Rippeth, Steve Thrope and Ric Williams. In several cases, their input has helped us to avoid mistakes in the text. However, the responsibility for any residual shortcomings rests squarely with us and we welcome notification by readers of any remaining errors.

We are also grateful to many colleagues and co-workers, including Gerben de Boer, Juan Brown, Byung Ho Choi, Mark Inall, Kevin Horsburgh, Jonah Steinbuck, David Townsend, Mike Behrenfeld, Clare Postlethwaite, Yueng-Djern Lenn, Flo Verspecht, Pat Hyder, Matthew Palmer, John Milliman, David Roberts, Oliver Ross and Alex Souza, for help in the acquisition and drawing of many of the figures, and Kay Lancaster for timely help in re-drafting and providing important finishing touches. Much of our use of satellite imagery comes courtesy of the UK Natural Environment Research Council's Earth Observation Data Acquisition and Analysis Service (NEODAAS) at the University of Dundee and at the Plymouth Marine Laboratory, with particular thanks to Peter Miller and Stelios Christodoulou.

Finally, we are pleased to acknowledge that all of our work is dependent on the ability to go to sea and make observations in often challenging conditions. This book would not have been possible without the professionalism and skills of the research vessel crews and technicians, on which we continue to rely.

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GUIDE TO THE BOOK AND HOW TO MAKE THE BEST USE OF IT

We anticipate that readers of this interdisciplinary book will be a mixture of students and researchers who come to the subject of the shelf seas from a wide range of scientific backgrounds. At one extreme will be students of mathematics and physics who know little of biology and, at the other, students of biological subjects who have not pursued physical sciences beyond high school level. In between will be a broad group of students, including many who have already embarked on courses in marine science, who have some background in both physical and biological sciences.

In writing the book, we have endeavoured to cater to individuals from these diverse backgrounds without compromising the presentation of the science. In particular, we have structured the chapters to allow readers from a mainly biological background to appreciate the essence of the physical processes without having to follow the detail of the sometimes intricate mathematical arguments. Key processes are explained in more intuitive ways in box sections, many with illustrative diagrams. At the end of each chapter, the essential points are recapitulated in a chapter summary. There is also a selection of problems, of varying difficulty, and suggestions for further reading at the end of each chapter. In order to help students of all backgrounds familiarise themselves with key terminology, a full glossary is given at the back of the book.

The first chapter is a general introduction to the shelf seas, explaining their relation to the global ocean, their socioeconomic importance, the history of shelf sea investigations and the observational techniques now used in studying them. In Chapter 2 we explore the various physical forcing mechanisms which drive the shelf seas, determine their structure and supply the vital radiation input to drive photosynthesis. There follow three chapters concerned with the fundamental science which underpins our subsequent exploration of shelf sea processes: Chapters 3 and 4 focus on the basic physics of fluid motion, while Chapter 5 is concerned with the aspects of biogeochemistry and plankton survival involved in the shelf seas.

The book then moves to explore the main domains/regimes of the shelf seas in a series of five chapters. The cross-shelf schematic illustration in Fig. G1 provides us with a guide to where each chapter is focused. In Chapter 6 we consider the processes controlling thermal stratification, the partitioning of the shelf in stratified and mixed regimes and the controls exerted by stratification on the growth of plankton. The crucial role of low levels of internal mixing in supporting phytoplankton growth in the interior of the stratified regions is explored in Chapter 7, while Chapter 8 focuses on the physical nature and biological implications of the fronts produced by variations in tidal mixing. In Chapter 9, we consider the regions of the shelf where freshwater inputs from rivers play a major role, and in Chapter 10 we look at the

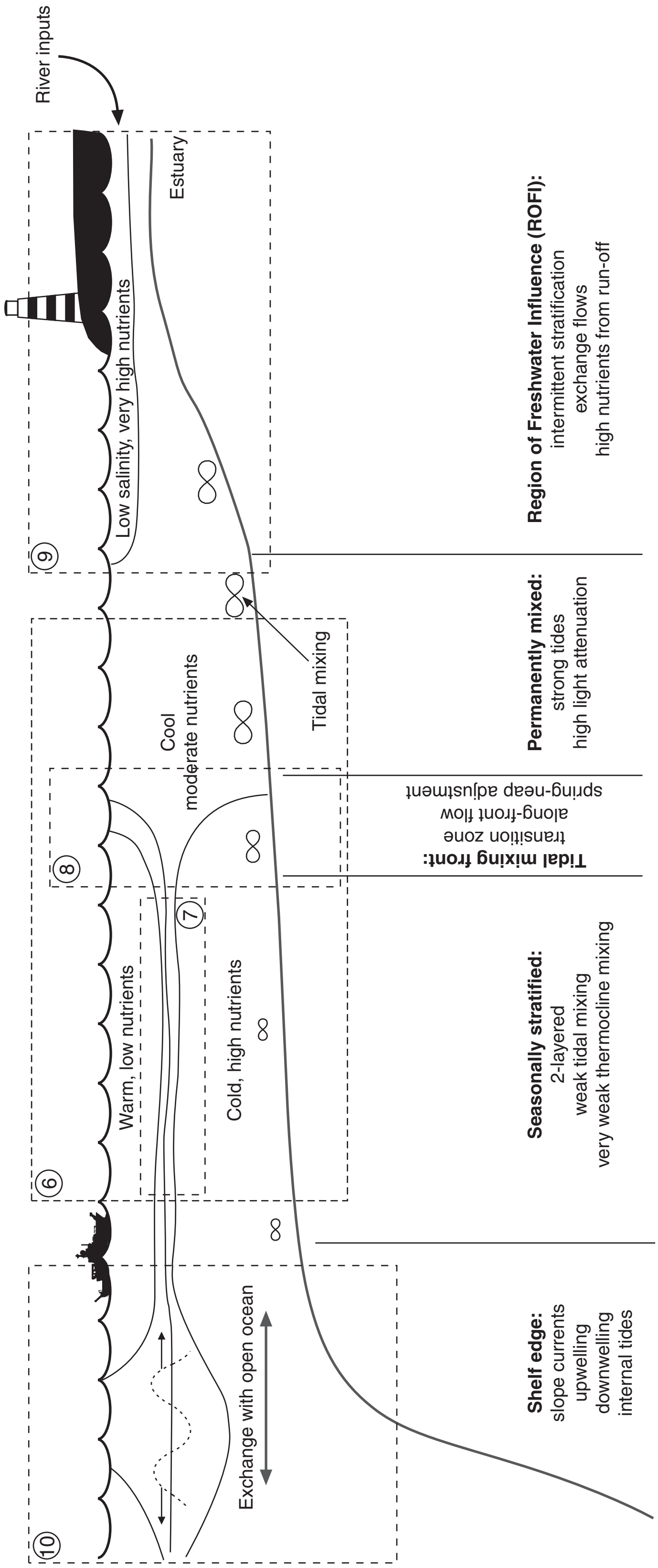

Figure G1 Schematic illustration of the shelf sea regimes. The dashed squares show the regions covered by individual chapters, with the relevant chapter number circled.

special physical processes of the shelf edge regime and their important biological consequences. The book concludes with an overview of progress and the remaining challenges in shelf seas, notably those in the Arctic and the tropics, and considers recent studies on the role of the shelf seas in relation to changes in the global ocean since the Pleistocene.

To help readers coming to the book from different disciplinary backgrounds, we offer a few suggestions on how best to approach it: Chapters 1 and 2 provide essential introductory background and should be readily accessible to all science students. For students who have already taken courses in physical oceanography, Chapters 3 and 4 may be largely revision but they will also be useful in applying knowledge of fluid physics to the shelf regime. Students without strong maths and physics may bypass some of the detailed argument here, certainly on a first reading, and make use of the boxes and summaries to pick up the essentials. Similarly, while much of Chapter 5 will already be familiar to students of biological oceanography, physics students will have a lot to learn here and may want to bypass some of the detail and, at least initially, rely on the summary. To help students identify the main points of the developing narrative, we have also put boxes around equations which are significant results to be applied in later sections or represent key stages in derivations. Students with previous training in both physical and biological marine science may want to bypass some of the tougher physics on first reading, returning later to follow the detail of the mathematics.

In addition to the problems for each chapter, many topics in the text are illustrated by visualisations and numerical models which are available on the book's website (http:www.cambridge.org/shelfseas). Much of the software is based on MATLAB and the programme scripts are available at the website for readers to copy, amend and use to explore their own ideas and understanding. The icon in the margin here is used throughout the book to indicate when there is relevant software on the book website.

SYMBOLS

Symbol	Name	Units
a	acceleration	m s^{-2}
a_e	Radius of the Earth	m
a_p	Phytoplankton cell radius	m
A	Albedo	none
A_0	Amplitude of oscillatory function	
A_n	Amplitude of tidal constituent	m
b	Buoyancy force per unit volume	N m^{-3}
$\mathbf{B}$	Buoyancy production of TKE	W kg^{-1}
B_G	Breadth of gulf	m
c	Phase velocity of waves	m s^{-1}
c_a	Specific heat of air	J kg^{-1} °C^{-1}
c_p	Specific heat of seawater	J kg^{-1} °C^{-1}
C	Conductivity	mS m^{-1}
C_d	Drag coefficient for wind stress	none
C_g	Geostrophic current speed	m s^{-1}
D	Ekman depth	m
e, e_s	Efficiency of mixing by tide and wind	none
E	Mass of the Earth	kg
E_d	Downward energy flux	W m^{-2}
E_k	Downward flux of PAR	W m^{-2}
Ek	Ekman number	
$E_s(k)$	Scalar spectrum for TKE	m^3 s^{-2}
E_T	Turbulent kinetic energy density	J kg^{-1}
E_v	Rate of evaporation	kg m^{-2} s^{-1}
$\mathbf{E_w}$	Energy density of waves	J m^{-2}
f	Coriolis parameter	s^{-1}
F	Force	N
$F(y)$	Function of variable y	
g	Acceleration due to gravity on Earth	m s^{-2}
g'	Reduced gravity	m s^{-2}
G	Gravitational constant	N m^2 kg^{-2}
$\underset{\sim}{G}$	Scalar flux vector	various
g_n	Phase lag of tidal constituent	degrees
g_p^b	Specific grazing rate	g C (g Chl)$^{-1}$ time^{-1}

List of symbols

Symbol	Name	Units
h	Water column depth	m
H_a	Attenuation factor for waves	none
H_n	Amplitude of a tidal constituent	m
H_T	Heat stored in water column	J m^{-2}
I	Total radiation energy flux	W m^{-2}
I_0	PAR flux incident at surface	μE m^{-2} s^{-1} or W m^{-2}
I_K	Saturation light level in photosynthesis	μE m^{-2} s^{-1} or W m^{-2}
$I_\lambda(\lambda)$	Spectral power density of radiation	W m^{-2} nm^{-1}
I_{PAR}	PAR flux at depth z	μE m^{-2} s^{-1} or W m^{-2}
J	Flux of a scalar property	various
k	Wave number	m^{-1}
k_b	Bottom drag coefficient	none
$k_b{}'$	Constant in a linear bottom drag law	m s^{-1}
k_m	Molecular diffusivity	m^2 s^{-1}
k_{NUT}	Half saturation concentration for nutrient uptake	mmol m^{-3}
k_s	Modified surface drag coefficient $= \gamma_s C_d$	none
K	Eddy diffusivity	m^2 s^{-1}
K_{av}	Spectral average of K_d	m^{-1}
K_d	Diffuse attenuation coefficient	m^{-1}
K_{PAR}	Attenuation coefficient for PAR	m^{-1}
K_q	Eddy diffusivity for TKE	m^2 s^{-1}
K_x,K_y	Horizontal Eddy diffusivity	m^2 s^{-1}
K_z	Vertical eddy diffusivity	m^2 s^{-1}
L	Turbulence length scale	m
L_H	Latent heat of evaporation	J kg^{-1}
L_O	Ozmidov length	m
L_S	Length scale for swimming plankton	m
m	Mass	kg
M	Mass of the moon	kg
M_s	Mass of a scalar substance	kg
N	Stability frequency	s^{-1}
N_z	Eddy viscosity	m^2 s^{-1}
p	Pressure	Pa
p_0	Atmospheric pressure	Pa
$\boldsymbol{P}$	Shear production of TKE	W kg^{-1}
P_a	Power available to produce TKE	W m^{-3}
P_{Chl}	Phytoplankton Chl biomass concentration	g Chl m^{-3}
P^b_{dark}	Specific growth rate in the dark	g C (g Chl)$^{-1}$ s^{-1}

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Symbol	Name	Units
Pe	Peclet number	none
P_p	Rate of primary production	g C m^{-3} s^{-1}
$P_p{}^b$	P_p normalised by Chl biomass = P_p/P_{Chl}	g C (g Chl)$^{-1}$ s^{-1}
P^b_{max}	Maximum value of $P_p{}^b$	g C (g Chl)$^{-1}$ s^{-1}
P_r	Ratio of N_z/K_z	none
P_S,P_N	Stirring power at springs/neaps position of a TM front	W m^{-3}
P_T,P_W	Stirring power of tidal flow and wind	W m^{-2}
$\boldsymbol{P_w}$	Energy flux in waves	W m^{-1}
q	Turbulent eddy speed	m s^{-1}
q_a	Specific humidity of air	none
q_s	Specific humidity at saturation	none
Q_b	Back radiation from sea surface	W m^{-2}
Q_c	Heat loss by conduction	W m^{-2}
Q_e	Evaporative heat loss	W m^{-2}
Q_i	Q_s (1−A) − Q_u	W m^{-2}
Q^N	Phytoplankton cell nutrient quota	mmol N (mg C)$^{-1}$
$Q^N{}_{max}$	Maximum cell nutrient quota	mmol N (mg C)$^{-1}$
$Q^N{}_{min}$	Minimum cell nutrient quota (subsistence quota)	mmol N (mg C)$^{-1}$
Q_s	Solar energy input to sea surface	W m^{-2}
Q_{sed}	Heat exchange with sediments	W m^{-2}
Q_u	$Q_b + Q_b + Q_c$ = total heat loss through sea surface	W m^{-2}
Q_v	Heat gain from horizontal advection	W m^{-2}
ΔQ	Quantity of heat input per unit area	J m^{-2}
r^b_p	Phytoplankton-specific respiration rate	C (g Chl) $^{-1}$ time^{-1}
r_{SM}	Ratio of constituents S_2 to M_2	none
R R'	Moon and Earth orbital radii about centre of gravity of Earth – Moon system	m
R_d	River discharge	m^3 s^{-1}
Re	Reynolds number	none
Rf	Flux form of the Richardson number	none
Ri	Richardson number	none
RN	Rossby number	none
Ro,Ro'	Rossby radius (external and internal)	m
R_w	Freshwater inflow per unit width	m^2 s^{-1}
s	Concentration of a scalar	various
S	Salinity (or generic scalar)	none
SH	Simpson-Hunter stratification parameter	$\log_{10}$(m^{-2}s^3)
S_M,S_H	Stability functions	none
S_v	Velocity shear	s^{-1}

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Symbol	Name	Units
t	Time	s
T	Temperature in Centigrade	°C
T_a	Air temperature	°C
T_b	Transport in bottom Ekman layer	$m^2 s^{-1}$
T_c	Period of a tidal constituent	s
T_E	Period of Earth's rotation	s
T_I	Inertial period	s
T_K	Kelvin temperature	°K
T_m	Vertical mixing time	s
T_p	Wave period	s
T_{res}	Residence time	s
T_s	Temperature of the sea surface	°C
$\boldsymbol{T_w}$	Kinetic energy density of waves	$J m^{-2}$
$\hat{u}, \hat{v}$	Depth-mean velocity components in x, y	$m s^{-1}$
u,v,w	Velocity components in x,y,z	$m s^{-1}$
u',v',w'	Turbulent velocity components	$m s^{-1}$
u_b,v_b	Velocity at bottom boundary	$m s^{-1}$
u_g	Geostrophic velocity	$m s^{-1}$
u_{max}	Maximum nutrient uptake rate	$nmol l^{-1} h^{-1}$
$u^v{}_{max}$	Cell volume–specific uptake rate	$mmol m^{-3} s^{-1}$
u_{NUT}	Uptake rate of nutrient during incubation	$nmol l^{-1} h^{-1}$
u_s	Surface current speed	$m s^{-1}$
U, V	Depth-integrated transports in x, y	$m s^{-1}$
U,V,W	Time average velocity components (Chapter 4)	$m s^{-1}$
U_g	Group velocity of waves	$m s^{-1}$
$\boldsymbol{V_w}$	Potential energy density of waves	$J m^{-2}$
v_c	Phytoplankton swimming speed	$m s^{-1}$
x,y,z	Cartesian coordinates	m
W	Wind speed	$m s^{-1}$
z'	Fractional depth z/h	none
z_{cr}	Critical depth	m
α	Thermal volume expansion coefficient	$°C^{-1}$
α_n	Phase of tidal constituent in TGF	radians
α_q	Maximum light utilisation coefficient	$g C (g Chl)^{-1} m^2 s \mu E^{-1} s^{-1}$
β	Salinity coefficient of density	none
γ	Compressibility of seawater	Pa^{-1}
γ_s	Ratio of surface current to wind speed	none
Γ	$R_f/(R_f + 1)$	none
δ	Angle	radians
ε	Rate of energy dissipation to heat	$W kg^{-1}$ or $W m^{-3}$

Symbol	Name	Units
ε_s	Emissivity	none
ζ	Vertical displacement	m
η	Surface elevation	m
η_v	Kolmogorov microscale	m
θ	Angle	radians
κ	von Kármán constant	none
λ	Wavelength	m
μ	molecular viscosity	N m^{-2} S
μ^N	Nutrient-dependent specific growth rate	$time^{-1}$
$\mu^N{}_{max}$	Maximum nutrient-dependent specific growth rate	$time^{-1}$
v	Kinematic viscosity	m^2 s^{-1}
ξ	Density gradient $= (1/\rho_0)\,\partial\rho/\partial x$	m^{-1}
ρ	Density of seawater	kg m^{-3}
$\hat{\rho}$	Depth-averaged density	kg m^{-3}
ρ_0	Reference density	kg m^{-3}
ρ_a	Density of air	kg m^{-3}
ρ_s	Surface density	kg m^{-3}
σ	Standard deviation of dispersion	m
σ_s	Stefan's constant	W m^{-2} K^{-4}
σ_{STP}	Density as ρ-1000	kg m^{-3}
σ_t	Density as ρ-1000 at zero pressure	kg m^{-3}
τ	Tangential stress	Pa
τ_b	Bottom stress	Pa
τ_W	Wind stress on sea surface	Pa
τ_x, τ_y	Horizontal stress components	Pa
ϕ	Velocity potential function	m^2 s^{-1}
ϕ_L	Latitude	degrees
Φ	Potential energy anomaly	J m^{-3}
χ	Surface slope $= \partial\eta/\partial x$	none
ψ	Angle	radians
$\Psi(\omega)$	Frequency spectrum of kinetic energy	m^2s^{-1}
ω	Angular frequency	s^{-1}
ω_a	Annual cycle angular frequency	s^{-1}
ω_n	Tidal constituent angular frequency	s^{-1}
Ω	Earth's angular speed of rotation	s^{-1}

Note: This list includes the principal symbols used in the book. You will find a number of additional symbols, which are used only locally and are defined at the point of use.