

## Changing Sea Levels

### Effects of Tides, Weather and Climate

The coastal zone is a dynamic environment of great social and economic importance. Flooding of coastal communities is one of the major causes of environmental disasters worldwide. Many coastal processes are driven and controlled by regular and by extreme variations in sea levels.

*Changing Sea Levels* is a basic sea level text for all related interdisciplinary studies. It presents an introduction to measurement techniques including satellite altimetry, tidal analysis and prediction, storm surges and flooding risks, and discusses how they are estimated. The author explains the concepts involved in understanding and forecasting future sea level changes and impacts. Examples and illustrations are drawn from all around the world, as befits the global nature of the topic.

Based on courses taught by the author in the University of Southampton and the Florida Institute of Technology, this book is aimed at undergraduate students at all levels. Students should have a general background in science. However, the text is developed so that non-basic mathematics is confined to appendices and a website (<http://publishing.cambridge.org/resources/0521532183/>). More advanced students are guided to extend their studies by wider reading. *Changing Sea Levels* will also interest and inform professionals in many fields including hydrographers, coastal engineers, geologists and biologists, as well as coastal planners and economists.

DAVID PUGH was awarded a Ph.D. in geodesy and geophysics from the University of Cambridge in 1968, and subsequently worked at the Proudman Oceanographic Laboratory, Merseyside. In 1984 he became Head of Oceanography, Hydrology and Meteorology, Science Division, UK Natural Environment Research Council. He has also served as Head of Information and Scientific Services in the Institute of Oceanographic Sciences (1987–92) and as Secretary to the United Kingdom Government Committee on Marine Science and Technology (1992–2003). He was elected President of the Intergovernmental Oceanographic Commission of UNESCO in July 2003, having previously been the Founding Chairman of the IOC Global Sea Level network, GLOSS. In addition to leading and serving many international organisations, Dr Pugh has maintained an active programme of research and teaching within the University of Southampton Oceanography Centre and as a Visiting Professor in the University of Liverpool. His interests include tides, surges, mean sea level, coastal management and climate change, the economics of marine activities related to GDP, and the history of sea level measurements. He is a Fellow of the Institute of Physics; the International Association of Geodesy; and the Institute of Marine Engineering, Science and Technology. He was awarded an OBE in the 2003 Queen's Birthday Honours for services to marine sciences. Dr Pugh is also the author of *Tides, Surges and Mean Sea-Level* (1996).

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## Contents

Preface	<i>page</i> ix
Acknowledgements	xi
List of symbols	xii
<b>1 Introduction and measurements</b>	<b>1</b>
1.1 Background	1
1.2 Changing sea levels	2
1.3 Historical ideas	7
1.4 Measuring sea levels	9
1.4.1 Datums	9
1.4.2 Direct surface measurements	13
1.4.3 Fixed sensors	16
1.4.4 Satellite altimetry	21
1.4.5 Data reduction and assimilation	25
Further reading	28
Questions	28
<b>2 Tidal forces and patterns</b>	<b>29</b>
2.1 Tidal diversity	29
2.2 Gravitational attraction	33
2.3 Tidal forces: a fuller description	37
2.3.1 The Equilibrium Tide	37
2.3.2 Solar tides	39
2.4 Tidal patterns	39
2.4.1 Diurnal tides	39
2.4.2 Spring–neap cycles	41
2.4.3 Nodal cycles	42
2.5 The geoid	43
Further reading	48
Questions	48
<b>3 Analysis and prediction</b>	<b>50</b>
3.1 Non-harmonic methods	51

## vi Contents

3.2	Basic statistics	52
3.3	Harmonic analysis	55
3.3.1	Basic concepts	55
3.3.2	Application of harmonic analysis	61
3.3.3	Accuracy of tidal constituents	63
3.3.4	Harmonic equivalents of some non-harmonic terms	64
3.3.5	Analysis of satellite altimetry data for harmonics	65
3.4	Response analysis	67
3.5	Analysis of currents	69
3.6	Tidal prediction	69
3.6.1	Reference or Standard Stations	69
3.6.2	Secondary or Subordinate Stations	71
	Further reading	74
	Questions	75
<b>4</b>	<b>Tidal dynamics</b>	<b>76</b>
4.1	Tides in the real world	76
4.2	Characteristics of long waves	78
4.2.1	Long-wave propagation	78
4.2.2	Standing waves and resonance	80
4.2.3	Long waves on a rotating earth	83
4.3	Ocean tides	86
4.4	Shelf tides	93
4.5	Internal tides	100
4.6	Tidal energy	103
	Further reading	106
	Questions	107
<b>5</b>	<b>Tides near the coast</b>	<b>108</b>
5.1	Hydrodynamic distortions	109
5.1.1	Bottom friction	109
5.1.2	Finite water depth	110
5.1.3	Flow curvature	111
5.2	Representation by higher harmonics	112
5.3	Southampton tides	114
5.4	Currents in channels	117
5.5	Tides in estuaries and rivers	119
5.5.1	Spring–neap effects	120
5.5.2	Tidal bores	121
5.6	Tidal energy: turbulence and dissipation	122
5.6.1	Bottom friction	122

5.6.2	Moving amphidromes	123
5.6.3	Tidal turbulence	125
	Further reading	128
	Questions	128
<b>6</b>	<b>Weather and other effects</b>	<b>129</b>
6.1	Background	130
6.2	Some statistics of meteorological residuals	131
6.3	Responses to atmospheric pressure	134
6.4	Responses to wind	136
6.4.1	Stress laws	137
6.4.2	Wind set-up	138
6.4.3	Ekman transport	139
6.5	Some regional examples of surges	141
6.6	Seiches	147
6.7	Tsunamis	149
	Further reading	155
	Questions	156
<b>7</b>	<b>Mean sea level</b>	<b>157</b>
7.1	Calculating mean sea level	159
7.2	Spatial changes in mean sea level	161
7.3	Observed annual and inter-annual changes	163
7.3.1	Seasonal (annual) changes	164
7.3.2	Air pressure effects	165
7.3.3	Ocean circulation	165
7.3.4	Nodal MSL changes	167
7.4	Isostatic adjustment	167
7.5	Changes of water volume	171
7.5.1	Thermal expansion	171
7.5.2	Melting ice	174
7.5.3	Other effects	175
7.6	Summary of recent MSL changes	175
	Further reading	178
	Questions	179
<b>8</b>	<b>Extreme sea levels</b>	<b>180</b>
8.1	Return periods and risk	180
8.2	Ways of estimating flooding risks	182
8.2.1	Regional factors	183
8.2.2	Annual maxima	183
8.2.3	Joint tide–surge probability estimates	185

## viii Contents

8.2.4	Other methods	188
8.3	Risks and climate change	188
8.3.1	Tidal changes	189
8.3.2	Trends in weather effects	189
8.3.3	Expected MSL changes	191
8.3.4	Combined effects on flooding risk	193
8.4	Responses to changing flooding risks	195
8.4.1	Impacts of changing sea levels	195
8.4.2	Is it worth paying for protection?	199
8.4.3	Examples of responses	201
	Further reading	206
	Questions	207
<b>9</b>	<b>Tidal influences</b>	<b>208</b>
9.1	Tidal inlets	208
9.1.1	Flow in tidal channels	209
9.1.2	Inlet cross-section and the tidal prism	211
9.2	Tidal asymmetry and sediment movements	212
9.3	Salt marshes and mangroves	213
9.4	Zonation of coastal plants and animals	214
9.4.1	Patterns of exposure and submersion	215
9.4.2	Rocky shores	218
9.4.3	Sedimentary shores	220
9.5	Behaviour adaptation	221
9.6	Mean sea level: the geological record	222
9.7	Tides past	224
9.8	Legal definitions of tidal boundaries	226
	Further reading	229
	Questions	230
	Appendix 1 Tidal potential	233
	Appendix 2 Answers to selected questions	236
	Glossary	241
	References	251
	Index	255

The colour plates are situated between pages 82 and 83.

## Preface

Our scientific conference in the Maldives on climate and sea level change was going well. As a break we were taken to meet a group of local people to hear their concerns for the future of their beautiful, yet low-lying and vulnerable tropical island Republic. A little to the side of the main demonstration of speeches and banners, a small boy held up high his homemade poster. It declared ‘Down with sea level rise’. Worldwide popular concern about possible global warming and sea level rise has been expressed in many ways, but rarely as simply or as effectively.

There is a sea level problem. It may affect, and should concern, us all. Political, economic and social responses need to be guided by scientific evidence and reliable interpretation of the processes involved.

This publication is an introduction to the necessary scientific assessments. It looks at sea level change in terms of the three main causes – astronomical tides, weather and climate trends. It is aimed at undergraduate students of all levels. More advanced students are guided to extend their studies by wider reading. It will also interest and inform professionals in many fields including hydrographers, coastal engineers, geologists, biologists and, perhaps, coastal planners, marine lawyers and economists.

This book began as a development from my earlier, still widely available but now out-of-print, book on *Tides, Surges and Mean Sea-Level*. The older book contains more detail on many topics, but this shorter and more basic book includes much new material, especially on satellite altimetry and climate change effects. My aim has been to reduce the mathematics to the minimum level necessary to describe the processes. More details are given in an appendix, and on the website that accompanies this book (<http://publishing.cambridge.org/resources/0521532183/>). This website will also update the Further reading sections at the end of each chapter. It includes detailed answers to the questions, which are intended to provoke discussion and extend the text, rather than to ensnare the reader in difficult calculations.

Starting to write a book is much easier than converging on the final product. My progress has been encouraged, advised and helped by many colleagues and friends. Foremost among these are Sylvia Allison, Isabel



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David Pugh

Frontmatter

[More information](#)

---

x Preface

Goncalves Araújo, Kate Davis, George Maul, Ana Paula Teles and, as ever, Philip Woodworth.

Others too have helped in many ways, providing additional information and illustrations. These include Carl Amos, Peter Challenor, Lee Harris, John Hunter, Christian Le Provost, Alex Mustard, Adrian New, Jonathan Sharples, Jose da Silva, Robert Smith, Helen Snaith and Alan Suskin. I am particularly grateful to students at Southampton University and the Florida Institute of Technology who helped road test early versions. These include Yasser Abualnaja, Abdullah Al-Subhi, William Carter, Frank Lesley, Natasha Labaume, Jeffrey Simmons and Ivan Haig. Specific acknowledgements are given as appropriate in the text.

Writing a book is a selfish activity. Once again I am indebted to Carole for allowing and even encouraging this indulgence. It has been written at home, in hotels and on planes travelling among five continents. As a result the examples and illustrations used are truly global, as are the issues this book addresses.

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## Symbols

$a$	earth radius
$c$	wave speed; $(gD)^{\frac{1}{2}}$ in shallow water
$C_a$	speed of sound in air
$C_e$	speed of electromagnetic wave
$C_D$	dimensionless drag coefficient
$D$	water depth
$d_l, d_s$	declinations of the moon and sun
$f$	Coriolis parameter $f = 2\omega_s \sin \phi$
$F$	a form factor which describes the relative importance of diurnal and semidiurnal tides at a particular location
$f_n$	nodal amplitude factor for harmonic constituent $n$
$g$	gravitational acceleration
$G$	universal gravitational constant
$g_n$	phase lag of harmonic constituent $n$ on the local Equilibrium Tide. Relative to the Equilibrium Tide at Greenwich, the symbol used is $G_n$ (usually expressed in degrees)
$H_n$	amplitude of harmonic constituent $n$ of tidal levels. $H_0$ is the amplitude of a Kelvin wave at the coast
$l$	length variable
$m_e, m_l, m_s$	mass of earth, moon, sun
$O(t)$	observed series of sea levels
$P$	general pressure variable
$P_A$	atmospheric pressure at the sea surface
$Q(z)$	probability of a level $z$ being exceeded in one year
$r$	distance, variously defined
$R$	Rossby radius
$S(t)$	meteorological surge component of sea level
$t$	time
$T(t)$	tidal component of sea level
$T_L$	design life of an engineering structure
$u$	current speed (often used for tidal currents)
$u_n$	nodal phase factor for harmonic constituent $n$

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David Pugh

Frontmatter

[More information](#)

## List of symbols xiii

$V_n$	nodal astronomical phase angle of harmonic constituent $n$ in the Equilibrium Tide, relative to the Greenwich Meridian
$W$	wind speed
$Z_0(t)$	mean sea level
$\zeta$	displacement of water level from the mean
$\rho$	seawater density
$\sigma$	standard deviation of a time series
$\phi$	latitude
$\omega_n$	angular speed of constituent $n$
$\omega_0$ to $\omega_6$	angular speeds of astronomical variables (see Table 3.2)
$\omega_s$	angular speed of the earth's rotation on its axis relative to a fixed celestial point ( $\omega_s = \omega_0 + \omega_3 = \omega_1 + \omega_2$ )