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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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

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.

Acknowledgements

The following figures are reprinted with permission from Elsevier, Copyright (2001). From *Sea Level Rise: History and Consequences* (edited by Douglas, Kearney and Leatherman), Figures 7.1, 7.7, 7.8 and 7.13 which appear in the original publication on pages 41, 173, 10 and 54. From *Satellite Altimetry and Earth Sciences* (edited by Fu and Cazenave), Figures 3.5, 4.16a and 7.3 which appear in the original publication on pages 271, 292 and 339.

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_o 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

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
ζ	displacement of water level from the mean
ρ	seawater density
σ	standard deviation of a time series
ϕ	latitude
ω_n	angular speed of constituent n
ω_0 to ω_6	angular speeds of astronomical variables (see Table 3.2)
ω_s	angular speed of the earth's rotation on its axis relative to a fixed celestial point ($\omega_s = \omega_0 + \omega_3 = \omega_1 + \omega_2$)