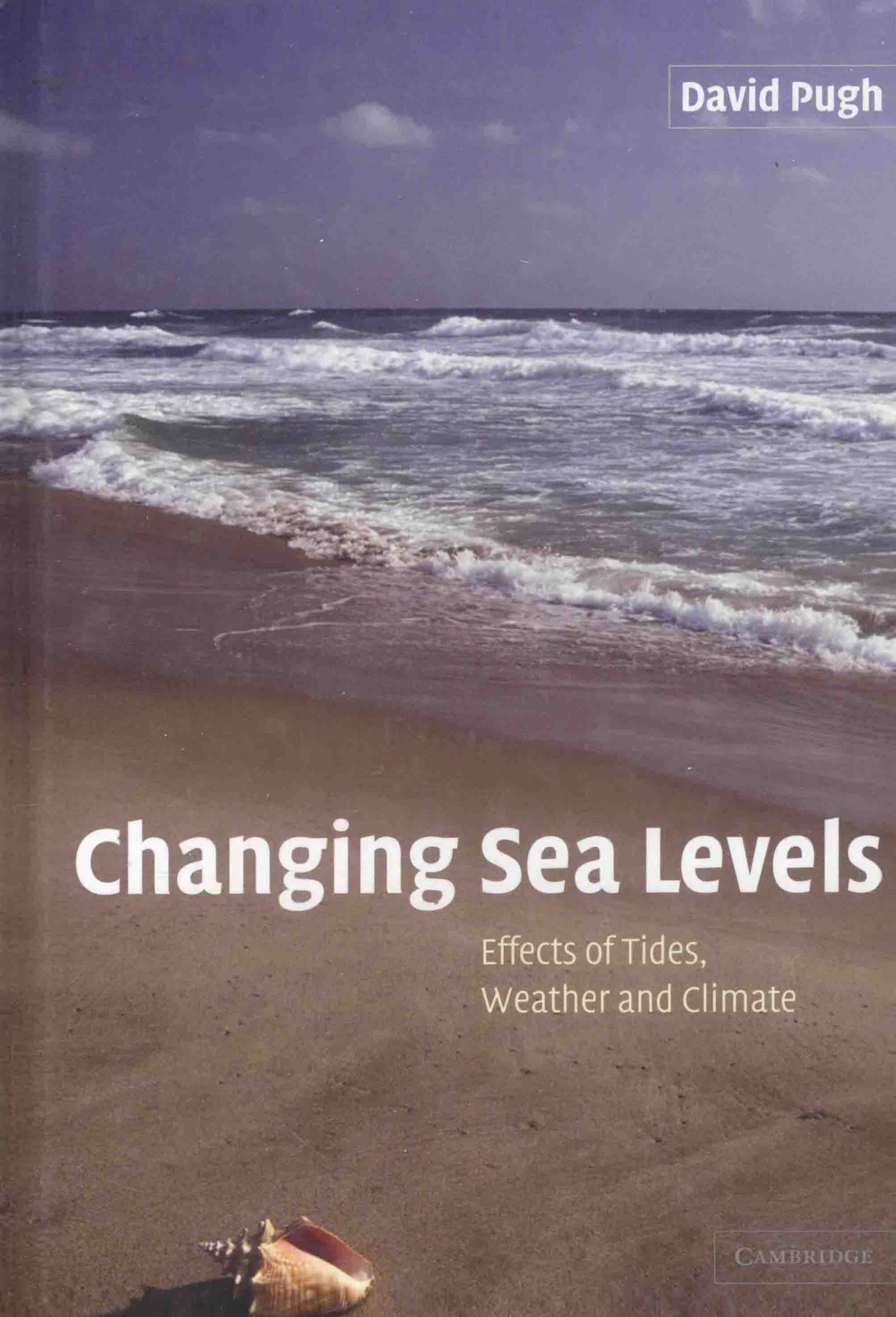

David Pugh

Changing Sea Levels

Effects of Tides, Weather and Climate

CAMBRIDGE

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge, CB2 2RU, UK
40 West 20th Street, New York, NY 10011–4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2004

Printed in the United Kingdom at the University Press, Cambridge

Typefaces Times NewRoman 10/13 pt. and StoneSans *System* LaTeX 2ε [TB]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data
Pugh, D. T.
Changing sea levels: effects of tides, weather and climate / David Pugh.
p. cm.
Includes bibliographical references and index.
ISBN 0 521 82532 6 – ISBN 0 521 53218 3 (paperback)
1. Sea levels. 2. Tides. 3. Storm surges. 4. Climatic changes – Environmental aspects.
I. Title.
GC89.P84 2004
551.45′8 – dc22 2003055752

ISBN 0 521 82532 6 hardback
ISBN 0 521 53218 3 paperback

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).

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 ($\omega_s = \omega_0 + \omega_3 = \omega_1 + \omega_2$)

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Chapter 1
Introduction and measurements

Sea levels are always changing, for many reasons. Some changes are rapid while others take place very slowly. The changes can be local or can extend globally. In this introductory chapter we establish some basic ideas of sea level change before looking at the various processes involved in more detail.

The first part of this chapter is an introduction to sea level science as we develop it in this book. It explains the importance of understanding sea level changes and outlines how sea levels are affected by a wide range of physical forces and processes. This is followed by a brief account of the development of ideas on the reasons why sea levels change. The second part is about ways of measuring sea levels. All studies of sea level should be based on reliable measurements over as long a period as possible: we outline the many methods that are available, and discuss their various advantages and disadvantages.

1.1 Background

Living by the sea has many benefits. It offers possibilities of trade and travel, and increasingly of water-based recreation. Natural geological processes have often conspired to create flat and fertile land near to the present sea level, to which people are drawn or driven to settle because the living is usually agreeable.

But there are risks. Sometimes high tides and storms combine to flood low-lying coastal regions causing local damage. Throughout history, humankind has adapted to periodic coastal flooding, but as our cities and our patterns of coastal development become more intricate, populated and interdependent, we become more and more vulnerable to disasters. The rural response of driving cattle to higher ground for the duration of a flood is much easier than the urban complexity of rebuilding complete sewerage and transport systems. In extreme cases the delicate infrastructure of coastal cities may be destroyed, with disastrous long-term consequences.

In November 1966, St Mark's Square in Venice was covered by more than one metre of water. It has been reported that in the first decades of the twentieth century, St Mark's Square was invaded by water seven times per year. By 1990, flooding occurred on average more than forty times a year. With a further 30 cm increase in average sea levels, St Mark's Square would be flooded on average 360 times a year, until defences are built to provide a higher level of protection.

In the long-term, defence is not always possible, nor is it always easy to justify protection in strict economic terms. For example, the Maldives Islands in the Indian Ocean are on average less than 2–3 m above sea level and the Government fears that the Republic's very survival may be threatened by global increases in sea level. Elsewhere, the delta regions of Bangladesh and Egypt are among the most densely populated on earth and the people who live there are especially vulnerable. Protection in these cases will be very difficult and expensive.

Humankind is only one of the biological species that has adapted to the challenging environmental conditions for survival in the coastal zone. Rocky shores are colonised in horizontal bands or zones by plants and animals that have adapted, and that can tolerate different degrees of immersion and exposure. Coral reefs, mangrove swamps and salt marshes are other areas of similar intense coastal biological activity and zonation.

To predict future changes and the impacts of human activity, it is necessary to have a full understanding of all the factors that influence sea levels at the coast. The first step is to make measurements of sea level over a long period, so that there are firm facts on which to base a scientific discussion.

1.2 Changing sea levels

Anyone who had the patience to measure sea levels at the coast for a whole year would find a very regular and rather unexciting pattern of changes. Figure 1.1 shows a year of monthly measurements at Newlyn, a small fishing and recreational port in the southwest corner of Britain. Newlyn sea levels will often be used in this book as examples for our analyses, because Newlyn has a very long record of accurate measurements. Figure 1.2 shows the Newlyn tide gauge location and the

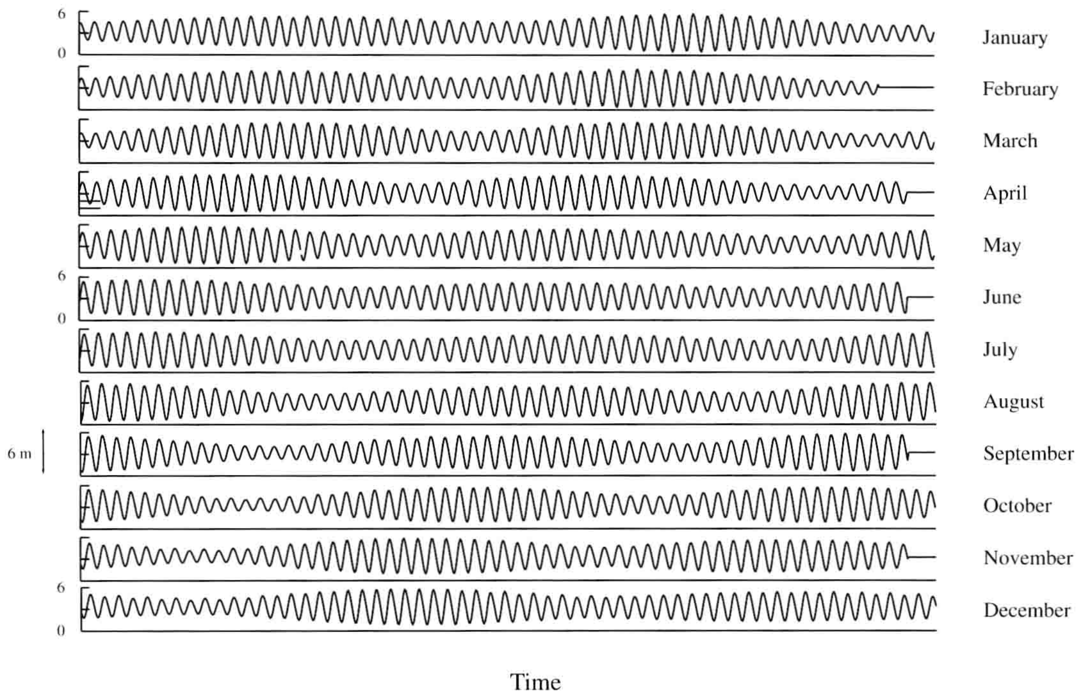
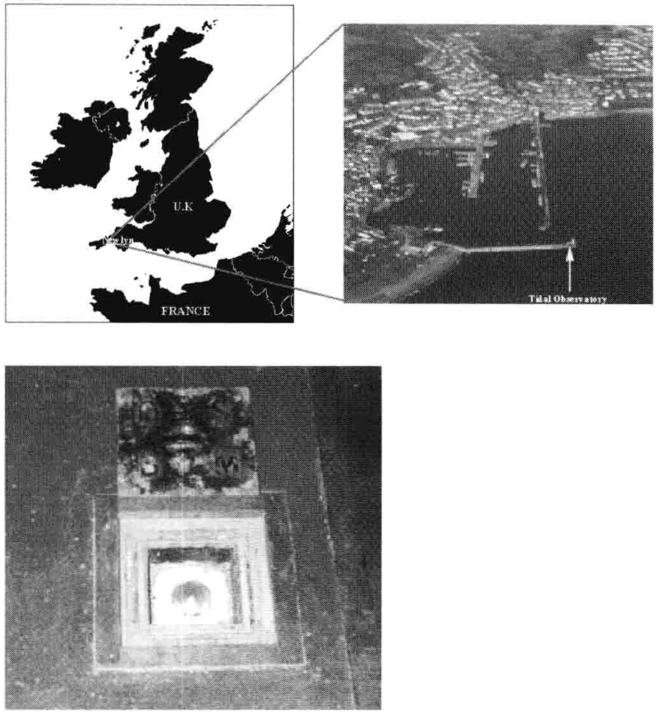


Figure 1.1. A year of sea level observations at Newlyn, southwest Britain, plotted month by month. The dominant semidiurnal tides and the spring–neap changes in range are evident.

benchmark, which defines the zero level for the measurements. The Newlyn benchmark is special: it is used to define the zero level for all British land levelling, based on the average, or mean sea level, over a long period (1915–21). The gauge, which was first installed for this purpose, has been well maintained since to establish a fundamental sea level data series.

Sea levels are changed by factors that extend over a wide range of space and time scales. Figure 1.3 is a space–time map of the main factors. It is drawn in terms of the time scales and the distance scales over which these factors operate. The approximate ranges of the variations associated with each effect are shown; the shapes plotted are only indicative, but note that tidal effects appear as narrow lines at times of one day and half a day. These are the diurnal and semidiurnal tides. Over long geological times, to the right of the diagram, many tectonic processes have changed land and sea levels; in the bottom left-hand corner, over much shorter periods of seconds, there are local wind waves.

In this book we will concentrate mainly on the sea level changes in between these two extremes – those that last from minutes to tens



(a) (b) (c)

Figure 1.2. The location (a) and harbour details (b) of the Newlyn tide gauge. Newlyn is separated from the Atlantic Ocean by 200 km of shallower continental shelf. The fundamental benchmark for land levelling datum definition in Britain is located alongside the gauge (c).

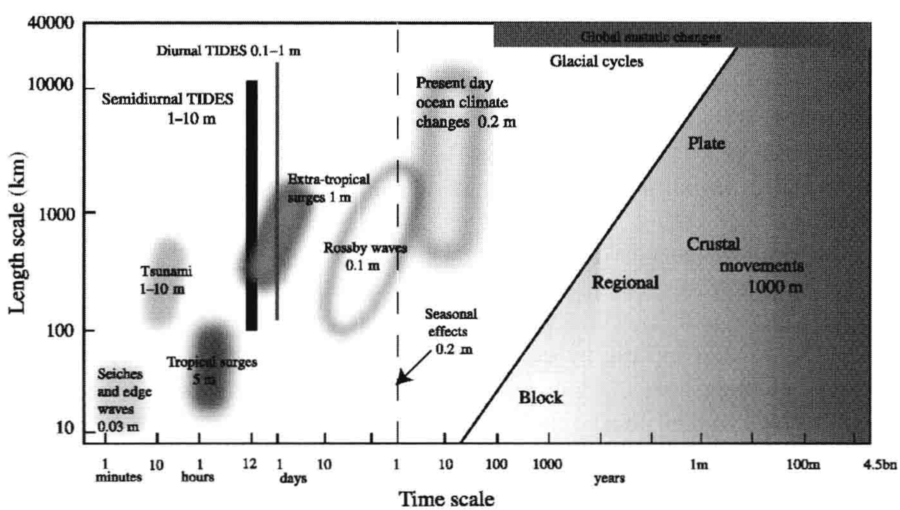


Figure 1.3. A map of the factors that change sea levels in space and time, with typical ranges in metres. Each of the factors discussed in this book occupies a different position on the map. Small-scale rapid changes are in the bottom left-hand corner.