DAVID PUGH AND
PHILIP WOODWORTH

SEA-LEVEL SCIENCE

Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes

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David Pugh and Philip Woodworth
National Oceanography Centre and University of Liverpool, UK

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Sea-Level Science

Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes

Sea levels change for many reasons and on many timescales, and extreme sea levels can result in catastrophic coastal flooding, such as the Katrina storm surge in 2005 or the Sumatra tsunami in 2004. As global sea level rises, and coastal populations increase, understanding sea-level processes becomes key to plan future coastal defence effectively.

Ocean tides, storm surges, tsunamis, El Niño and the sea-level rise caused by climate change are among the processes explained in this book. Building on David Pugh's classic graduate-level book *Tides, Surges and Mean Sea-Level*, this substantially updated and expanded full-colour book now incorporates major recent technological advances in the areas of satellite altimetry and other geodetic techniques (particularly GPS), tsunami science, measurement of mean sea level and analyses of extreme sea levels. The authors, both leading international experts, discuss how each surveying and measuring technique complements others in providing an understanding of present-day sea-level change and more reliable forecasts of future changes.

Giving the *how* and the *why* of sea-level change on timescales from hours to centuries, this authoritative and exciting book is ideal for graduate students and researchers working in oceanography, marine engineering, geodesy, marine geology, marine biology and climatology. It will also be of key interest to coastal engineers and governmental policy-makers.

David Pugh is a marine science consultant, also holding positions as Visiting Professor at the University of Liverpool and Visiting Scientist at the National Oceanography Centre (NOC). His research specialises in tides, surges, mean sea level, coastal management and climate change, together with marine economics and the history of sea level. After a career in science and science management with the UK Natural Environment Research Council, Dr Pugh served as President of the Intergovernmental Oceanographic Commission (IOC) of UNESCO, 2003–7. He had previously been Director of the Permanent Service for Mean Sea Level and Founding Chairman of the IOC Global Sea Level network, GLOSS. Dr Pugh has authored two books and recently co-edited *Troubled Waters: Ocean Science and Governance* (Cambridge University Press, 2010) published for the 50th anniversary of the IOC. He has been awarded an OBE for services to marine sciences.

Philip Woodworth is an Individual Merit Scientist in the Natural Environmental Research Council based at the NOC in Liverpool, and also a Visiting Professor at the University of Liverpool. He has been Director of the PSMSL and Chairman of GLOSS. Dr Woodworth has published extensively on tides, sea-level changes and geodesy, including co-editing *Understanding Sea-Level Rise and Variability* (Wiley Blackwell, 2010), and has been involved in each IPCC research assessment. His awards include the Denny Medal of IMAREST, the Vening Meinesz Medal of the European Geosciences Union, the 50th Anniversary Medal of the IOC, and a minute share in the 2007 Nobel Peace Prize awarded to the IPCC. He was awarded an MBE in 2011 for services to science.

'Governments and their planners responsible for management and defences against coastal flooding need the best science to identify present and future risks. This authoritative new book gives an excellent and comprehensive account of the science which underpins our understanding of sea levels, and its practical application on our changing planet.'

Wendy Watson-Wright, *Executive Secretary, Intergovernmental Oceanographic Commission of UNESCO*

'Professors Pugh and Woodworth's book is timely, authoritative, and will certainly have a prominent place on my bookshelf. It is a unique resource for teachers of upper undergraduate to graduate level courses, and will also be used often by sea-level researchers, coastal engineers and planners, and by many others with an interest in sea level.'

Gary T. Mitchum, *Professor and Associate Dean, College of Marine Science, University of South Florida, USA, and Chair of the Global Sea Level Observing System*

Preface

We spend much of our time studying sea-level science, a wide-ranging and constantly fascinating subject. We analyse data, read and write papers, and present findings at conferences where there are people in the same sea-level community as us. However, every so often we get to meet other people who have been exposed to this subject in a more personal way: someone who lost relatives in the 1953 North Sea storm surge, another who lost everything more than once in Bangladesh floods, a colleague who survived the 2004 Sumatra tsunami.

We remember at a conference of sea-level experts in the Maldives some years ago a small boy holding a homemade poster declaring 'Down with sea-level rise', as he feared for the future of his country. Concern about possible global warming and sea-level rise has rarely been expressed as simply or as effectively. These examples remind us that the results of our work are important, not just for the scientific papers that are produced, but also for many practical reasons, which somehow we find reassuring.

This book is an integrated account of sea level and the physical reasons why it is endlessly changing: tides, weather effects, tsunamis, long-term climate change, and even changes in the solid Earth. The chapters cover many fields: oceanography, geology, geodesy, climate change, coastal engineering, data management and others.

It takes as its starting point David Pugh's 1987 *Tides, Surges and Mean Sea-Level*, which is now long out of print, and significantly out of date. That book was published at a time of renaissance for sea-level science – a rebirth driven by the technology of satellites and ever more powerful computers; and by fundamental public concerns about the effects of climate change and potential increased coastal flooding. These concerns have been reinforced by recent catastrophic tsunami and storm surge events.

This new account has roughly three components. The first component consists of six chapters that follow the 1987 book's treatment of tides: instruments, forces, analysis and dynamics. In the second component, spanning Chapters 7 to 11, we review the major new developments in sea-level science: weather effects, tsunamis, satellites and geodesy, and global sea-level changes related to climate change. Our discussion of the latter can be read alongside the recently published *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, which provides even more facts and figures on sea level and climate.

In the third component, containing the final two chapters, we discuss more generally how humankind has been affected by changes in sea level in the past, and seeks to make practical arrangements for changes in the future. It is undoubtedly the case that changes in sea level affect the way we live our lives today, and they will become increasingly important in the future. Sea-level science matters to us all.

Acknowledgements

We are grateful for the help of many scientific colleagues and friends, who were kind enough to comment on early versions of each chapter and provide valuable advice. Particular thanks go to Trevor Baker, John Hunter, Alexander Rabinovich and Richard Ray, whose expertise on ocean and earth tides, sea-level extremes and tsunamis was so freely made available to us.

Several of our colleagues at the National Oceanography Centre were imposed upon to read draft chapters or advise on others. Special thanks go to Angela Hibbert, Miguel Angel Morales Maqueda, Jo Williams, Simon Williams and Judith Wolf.

We have also appreciated specific guidance and help from Thorkild Aarup, Yasser Abualnaja, Ole Andersen, Isabel Goncalves Araújo, Richard Bingley, David Blackman, David Cotton, Roland Gehrels, Jonathan Gregory, Ivan Haigh, Lee Harris, Kevin Horsburgh, John Howarth, Chris Hughes, Paul Hughes, John Huthnance, Antony Joseph, Mark Lawless, David Long, Mark Merrifield, Glenn Milne, Andy Plater, Rui Ponte, Reiner Rummel, Mikis Tsimplis, Javier Valladares, Ian Vassie, Ric Williams and Chris Wilson. We are also grateful for help and advice from our colleagues in the Permanent Service for Mean Sea Level: Lesley Rickards, Simon Holgate, Svetlana Jevrejeva, Mark Tamisiea, Andy Matthews, Kathy Gordon and Liz Bradshaw.

Other colleagues provided us with top copies of figures from their work or helped us find photographs. In some cases, the figures provided were unpublished ones, as we have acknowledged appropriately in the captions.

Robert Smith and Kate Davis have advised on and prepared many of the figures. We acknowledge the use of the Generic Mapping Tools package for others. The quotations in Chapters 6, 12 and 13 are reproduced with permission.

Acronyms

ACC	Antarctic Circumpolar Current
ADCP	Acoustic Doppler Current Profiler
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AO	Arctic Oscillation
AOGCM	Atmosphere–Ocean General Circulation Model
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
BM	Bench Mark
BP	Before Present or Bottom Pressure
BPR	Bottom Pressure Recorder
CGPS	Continuous GPS
CM	Centre of Mass
DART	Deep-ocean Assessment and Reporting of Tsunami
DD	Double Differencing (GPS data processing method)
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DNA	Deoxyribonucleic acid
ECDIS	Electronic Chart Display and Information System
EGPS	Epochal or Episodic GPS
EKE	Eddy Kinetic Energy
ENSO	El Niño–Southern Oscillation
Envisat	Environmental Satellite of the European Space Agency
EOF	Empirical Orthogonal Function
EOP	Earth Orientation Parameter
ERS-1, -2	European Remote Sensing satellite-1 and -2
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FBM	Fundamental Bench Mark
GCN	GLOSS Core Network
GCOS	Global Climate Observing System
GEOSS	Global Earth Observation System of Systems
GEV	Generalised Extreme Value
GFO	GeoSat Follow-on Satellite
GGOS	Global Geodetic Observing System (of the International Association of Geodesy)
GIA	Glacial Isostatic Adjustment
GLONASS	Global Orbiting Navigation Satellite System
GLOSS	Global Sea Level Observing System (of the Intergovernmental Oceanographic Commission)
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer Satellite
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment Satellite
GTS	Global Telecommunications System
HAT	Highest Astronomical Tide
IAG	International Association of Geodesy
IB	Inverse Barometer
ICESat	Ice, Cloud and Land Elevation Satellite
IERS	International Earth Rotation Service
IHO	International Hydrographic Organization
IGS	International GNSS Service
InSAR	Interferometric Synthetic Aperture Radar
IOC	Intergovernmental Oceanographic Commission

IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ITRF	International Terrestrial Reference Frame
IWO	Initial Withdrawal of the Ocean
JCOMM	WMO/IOC Joint Technical Commission for Oceanography and Marine Meteorology
LAT	Lowest Astronomical Tide
LEO	Low Earth Orbit
LGM	Last Glacial Maximum
LIB	Local Inverse Barometer
LOD	Length Of Day
MDT	Mean Dynamic Topography
MH[L]W	Mean High [or Low] Water
MH[L]WN	Mean High [or Low] Water Neaps
MH[L]WS	Mean High [or Low] Water Springs
MSL	Mean Sea Level
MSS	Mean Sea Surface
MTL	Mean Tide Level
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
NLSW	Non-Linear Shallow-Water equations
NOC	National Oceanography Centre (UK)
OTL	Ocean Tidal Loading
PDO	Pacific Decadal Oscillation
PGR	Post Glacial Rebound (now usually referred to as GIA)
POT	Peak Over Threshold
PPP	Precise Point Positioning (GPS data processing method)
PSMSL	Permanent Service for Mean Sea Level
PTWC/S	Pacific Tsunami Warning Center/System
RLR	Revised Local Reference data set of the PSMSL
SAM	Southern Annular Mode
SLR	Satellite Laser Ranging or Sea Level Rise
SOI	Southern Oscillation Index
SSH	Sea Surface Height
SST	Satellite-to-Satellite Tracking or Sea Surface Temperature
SWH	Significant Wave Height
TAR	IPCC Third Assessment Report
TEC	Total Electron Content
TG	Tide Gauge
TGBM	Tide Gauge Bench Mark
TIGA	TIde GAuge benchmark monitoring project of the IGS
TNT	Trinitrotoluene (a ton of TNT being a measure of explosive energy)
TOPEX/Poseidon	TOPography EXperiment/Poseidon radar altimeter satellite
UHSLC	University of Hawaii Sea Level Center
UNESCO	United Nations Educational, Scientific and Cultural Organization
VLBI	Very Long Baseline Interferometry
WAIS	West Antarctic Ice Sheet
WMO	World Meteorological Organization

Main symbols

a	Earth radius
A_l, A_s	right ascensions of the Moon and Sun
c	wave speed: $c = \sqrt{gD}$ in shallow water
C_l, C_s	hour angles of the Moon and Sun
C_a	speed of sound in air
C_e	speed of electromagnetic wave
D	water depth
d_l, d_s	declinations of the Moon and Sun
e_l, e_e	eccentricity of lunar and Earth orbits
f	Coriolis parameter $f = 2w_s \sin \phi$
F	a form factor that describes the relative importance of diurnal and semidiurnal tides at a particular location
f_n	nodal amplitude factor for harmonic constituent n
F_s, F_b	surface and bottom stresses in the X direction
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)
g_C, g_{AC}	phases of clockwise and anticlockwise components of current
g_{ux}, g_{vx}	phases of Cartesian current components
G_s, G_b	surface and bottom stresses in the Y direction
h	geocentric mean ecliptic longitude of the Sun
H_n	amplitude of harmonic constituent n of tidal levels
H_o	the amplitude of a Kelvin wave at the coast
i, j	general integers
l	length variable, spherical harmonic degree
L	length of ocean basin, maximum spherical harmonic degree
m_e, m_l, m_s	mass of Earth, Moon, Sun
N	ascending nodal lunar longitude
$O(t)$	observed series of sea levels (also $X(t)$)
p	longitude of lunar perigee
p'	longitude of solar perigee
P	general pressure variable
P_A	atmospheric pressure at the sea surface
P_z	pressure at depth z
Q_C, Q_{AC}	amplitudes of clockwise and anticlockwise components of currents
q	current speed
r	distance, variously defined
R_l, R_s	lunar and solar distances from the Earth
$R(t)$	residual non-tidal component of sea level
s	geocentric mean ecliptic longitude of the Moon
t	time
$T(t)$	tidal component of sea level
u, v	current components in the X and Y directions
u_n	nodal phase factor for harmonic constituent n
V_n	astronomical phase angle of harmonic constituent n in the Equilibrium Tide, relative to the Greenwich meridian
W	wind speed
x, y, z	coordinates of a point
X, Y, Z	Cartesian coordinate system. Z is positive vertically upwards
$X(t)$	observed series of sea levels (also $O(t)$)
Z_0	mean sea level
α	dimensionless ratio variously defined
ε_l, ε_s	ecliptic latitudes of the Moon and Sun
β	a general angular measure
ζ	displacement of water level from the mean
θ	direction to which current and wind flow, usually measured clockwise from north
λ_l, λ_s	true ecliptic longitudes of the Moon and Sun

ρ	seawater density
ρ_A	air density
σ_n	angular speed of constituent n, in degrees per mean solar hour
τ_s, τ_b	surface and bottom stresses
σ	standard deviation of a time series
Υ	First Point of Aries
ϕ	latitude of a point on the Earth's surface
ω_n	angular speed of constituent n in radians per mean solar hour
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 ($\omega_s = \omega_0 + \omega_3 = \omega_1 + \omega_2$)
Ω	Equilibrium tidal potential

Harmonic constituents are shown in heavy type thus: $\mathbf{X_2}$, to denote their vector property (H_x, g_x). Overbars denote time-averaged values.

Contents

Chapter

1 Introduction

Prospero: '. . .ye that on the sands with printless foot
Do chase the ebbing Neptune and do fly him
When he comes back'

Shakespeare, The Tempest

Sea levels are always changing, for many reasons. Some changes are rapid while others take place very slowly. The changes can be local, or extend globally. This book is about the science of these changes.

In this first chapter we outline what constitutes sea-level science. A brief account of the development of scientific ideas is followed by an outline of how sea levels are affected by a wide range of physical forces and processes. Finally we give some basic definitions, and discuss the fundamental statistics of sea levels as time series.

1.1 Background

Living by the sea has many benefits. Statistics show that about half the global population lives within 100 km of the sea. Most of the world's largest cities are on or near the ocean. Ninety per cent of all global trade is carried by sea. The coast offers possibilities of both 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.

There are risks. Throughout history, humankind has adjusted and coped with changing sea levels: the ebb and flow of the tides, storm flooding and, for some vulnerable places, the dangers of being inundated by a tsunami. However, 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 sewage and transport systems. In extreme cases flooding, with disastrous long-term consequences, may destroy the delicate infrastructure of coastal cities.

Books dealing with the science of sea levels and tidal phenomena are comparatively rare. However, unified treatments of general interest are found in older specialist books [1, 2, 3], and in more recent publications [4, 5, 6]. Accounts are also found in more general books on oceanography, especially the second volume of Defant's *Physical Oceanography* [7]. Defant and some other experts have also written more popular accounts [8], which are useful introductions, though sometimes hard to find.

1.2 Early ideas and observations

The link between the Moon and tides was known from very early times. Sailors had a very practical need for developing this understanding, particularly for their near-shore navigation in the small ships of those times. A more scientific explanation of the links between tides and the movements of the Moon and Sun evolved much later. Many eminent scientists have been involved in this scientific development.

Even 2000 years ago, historical records show an impressive collection of observed tidal patterns [9]. However, the ideas advanced by the philosophers of that time, and for the following 1600 years, to explain the connection between the Moon and the tides were less valid. Chinese ideas supposed water to be the blood of the Earth, with tides as its beating pulse, with the Earth breathing causing the tides. Arabic explanations supposed the Moon's rays to be reflected off rocks at the bottom of sea, thus heating and expanding the water, which then rolled in waves towards the shore. One poetic explanation invoked an angel who was set over the seas: when he placed his foot in the sea the flow of the tide began, but when he raised it, the tidal ebb followed. During this long period there was a decline in critical thought, so that the clear factual statements by the classical writers were gradually replaced by a confusion of supposed facts and ideas. One notable exception was the Venerable Bede, a Northumbrian monk, who described around AD 730 how the rise of the water along one coast of the British Isles coincided with a fall elsewhere. Bede also knew of the progression in the time of high tide from north to south along the Northumbrian coast.

Johannes Kepler (1596–1650), while developing laws to describe the orbits of the planets around the Sun, suggested that the gravitational pull of the Moon on the oceans might be responsible for tides. Isaac Newton (1642–1727) took this idea much further. Almost incidentally to the main insights of his *Principia* published in 1687 (the fundamental laws of motion, and the concept of universal gravitational attraction between bodies), Newton showed why there are two tides a day, and why the relative positions of the Moon and Sun are important. His contemporary, Edmond Halley (1656–1742, Figure 1.1), made systematic measurements at sea and prepared a map of tidal streams in the English Channel. Halley had encouraged Newton's work, paid for the publication of the *Principia* himself, and prepared an account of the tides based on Newton's theories [10]. Many other scientists extended and improved Newton's fundamental understanding, but it remains the basis for all later developments.

Figure 1.1 Edmond Halley (1656–1742) assisted in the publication of Newton's *Principia*, the basis for tidal science, and also led the first systematic tidal survey, of currents in the English Channel. © The Royal Society.

Daniel Bernoulli (1700–1782) published ideas about an Equilibrium Tide, which we shall look at in detail in Chapter 3. The Marquis de Laplace (1749–1827) developed theories of a dynamic ocean response to tidal forces on a rotating Earth, and expressed them in periodic mathematical terms. Thomas Young (1773–1829), while developing his theory on the wave characteristics of light, showed how the propagation of tidal waves could be represented on charts as a series of co-tidal lines.

The first operational automatic tide gauge and stilling-well system for measuring sea levels was installed at Sheerness in the Thames Estuary in 1831, to provide continuous sea-level data. These measurements in turn stimulated a new enthusiasm for tidal analysis and the regular publication by British authorities of annual tidal predictions to assist mariners to plan safer navigation. Even before the official tables, tidal predictions were published commercially, sometimes based on undisclosed formulae, for example those of the Holden family in northwest England [11].

Lord Kelvin (1824–1907) showed in detail how tides could be represented as the sum of periodic mathematical terms, and promoted a machine (Figure 4.12) that applied this idea for tidal predictions. He also developed mathematical equations for the propagation of tidal waves on a rotating Earth, in a form known as *Kelvin waves*. In 1867 the Coast Survey of the United States took responsibility for the annual production of official national tide tables. By the beginning of the twentieth century, most major maritime countries around the world began to prepare and publish regular annual official tide tables.

Meanwhile, other factors that influence sea-level changes were being investigated. James Clark Ross (1800–62) made sea-level measurements when trapped in the ice during the Arctic winter of 1848–9, and confirmed the already-known link between higher atmospheric pressures and lower sea levels. Earlier Ross had helped establish Tide Gauge Bench Marks in Tasmania and the Falkland Islands, as datums for scientific mean sea level studies during his voyage of exploration in the Southern Ocean. Establishing these fundamental fixed datum levels was done on the advice of the German geophysicist Alexander von Humboldt (1769–1859).

Harris [9] gives an extensive late-nineteenth-century historical account of early tidal ideas; Wheeler [12] gives a contemporary hydraulic engineering perspective. More recently, Cartwright [13] gives a comprehensive analysis of the scientific history of tides. A more general discussion of sea-level science and its place in the overall development of marine science is given in Deacon [14]; Reidy [15] describes the role of the British Admiralty in tidal science and its application.

1.3 Tidal patterns

Before the development of appropriate instrumentation, sea-level observations were confined to the coast and were not very accurate. Modern measuring systems, many of which will be described in the next chapter, have enabled a systematic collection of sea-level data which shows that regular water movements are a feature on all the shores of the oceans and of their adjacent seas. These regular tidal water movements are seen as both the vertical rise and fall of sea level, and as the horizontal ebb and flow of the water.

The tidal responses of the ocean to the forcing of the Moon and Sun are very complicated and tidal features vary greatly from one site to another. The two main tidal features of any sea-level record are the tidal range, measured as the height between successive high and low levels, and the period, the time between one high (or low) level and the next high (or low) level. Figure 1.2a, which shows the tides for March 2043 at five sites, clearly illustrates this variability. Figure 1.2b shows the lunar variables for the same month. The details of the relationships between the tides and the movements of the Moon and Sun are developed in Chapter 3. In this section we describe the observed sea-level variations at these five sites and relate them to the astronomy in a more general way.

We can now look in detail at Figure 1.2a. In most of the world's oceans the dominant tidal pattern is similar to that shown for Bermuda in the North Atlantic, and for Mombasa on the African shore of the Indian Ocean. Each tidal cycle takes an average of 12 hours 25 minutes, so that two tidal cycles occur for each lunar or moon day (every 24 hours 50 minutes). Because each tidal cycle occupies roughly half of a day, this type of tide is called *semidiurnal*. Semidiurnal tides have a range that typically increases and decreases cyclically over a 14-day period. The maximum ranges, called *spring tides*, occur a few days after both new and full Moons (syzygy, when the Moon, Earth and Sun are in line), whereas the minimum ranges, called *neap tides*, occur shortly after the times of the first and last quarters (lunar quadrature). The relationship between tidal ranges and the phase of the Moon is due to the additional tide-raising attraction of the Sun, which reinforces the Moon's tides at syzygy, but reduces them at quadrature. The astronomical cycles are discussed in detail in Chapter 3, but Figure 1.2b shows that when the Moon is at its maximum distance from the Earth, known as lunar apogee, semidiurnal tidal ranges are less than when the Moon is at its nearest approach, known as lunar perigee. This cycle in the Moon's motion is repeated every 27.55 solar days. Maximum semidiurnal ranges occur when spring tides (syzygy) coincide with lunar perigee [3], whereas minimum semidiurnal ranges occur when neap tides (quadrature) coincide with lunar apogee. Globally, semidiurnal tidal ranges increase and decrease at roughly the same time everywhere, but there are significant local differences. The maximum semidiurnal tidal ranges occur in semi-enclosed seas. In the Minas Basin in the Bay of Fundy (Canada), the semidiurnal North Atlantic tides at Burncoat Head have a mean spring range of 12.9 m. Equally large ranges are found in Ungava Bay, northeast Canada (see Chapter 5). The mean spring ranges at Avonmouth in the Bristol Channel (United Kingdom) and at Granville in the Gulf of St Malo (France) are 12.2 m and 11.3 m respectively. In Argentina the Puerto Gallegos mean spring tidal range is 10.4 m; at the Indian port of Bhavnagar in the Gulf of Cambay it is 8.8 m; and the Korean port of Inchon has a mean spring range of 8.4 m. More generally, however, in the main oceans the semidiurnal mean spring tidal range is usually less than 2 m.

Close examination of the tidal patterns at Bermuda and Mombasa in Figure 1.2a shows that at certain times in the lunar month the high water levels are alternately higher and lower than the average. This behaviour is also observed for the low water levels, the differences being most pronounced when

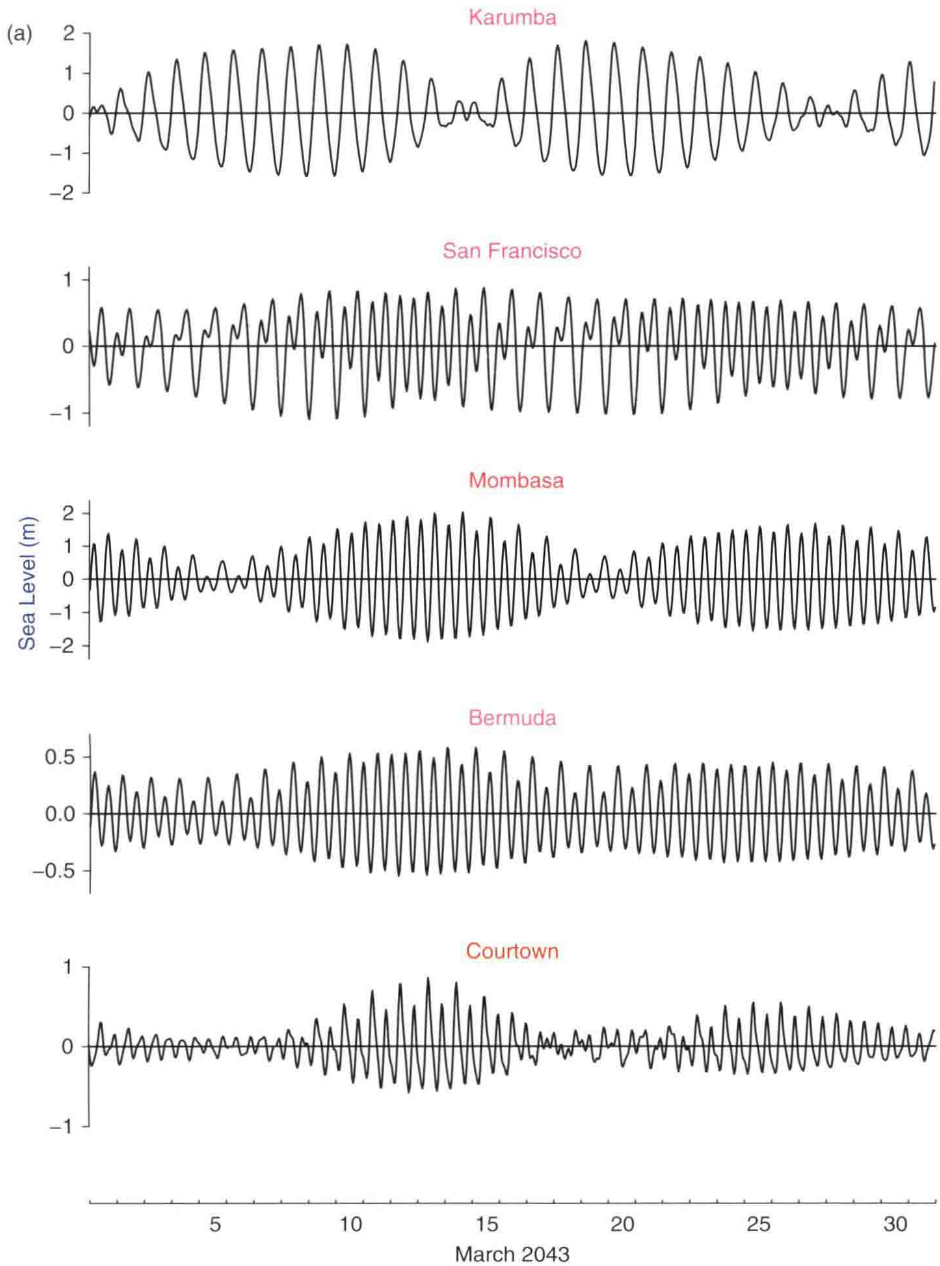

Figure 1.2 (a) Tidal predictions for March 2043 at five sites that have very different tidal régimes. At Karumba, Australia, the tides are diurnal, at San Francisco, United States, they are mixed, whereas at both Mombasa, Kenya, and Bermuda, semidiurnal tides are dominant. The tides at Courtown, Ireland, are strongly distorted by the influence of the shallow waters of the Irish Sea.

the Moon's declination north and south of the equator is greatest. The differences can be accounted for by a small additional tide with a period close to one day, which adds to one high water level but subtracts from the next one. In Chapters 3 and 4 we shall develop the idea of a superposition of several partial tides to produce the observed sea-level variations at any particular location.

In the case of the tide at San Francisco, the tides with a one-day period, which are called *diurnal tides*, are similar in magnitude to the semidiurnal tides. This composite type of tidal régime is called a mixed tide,