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

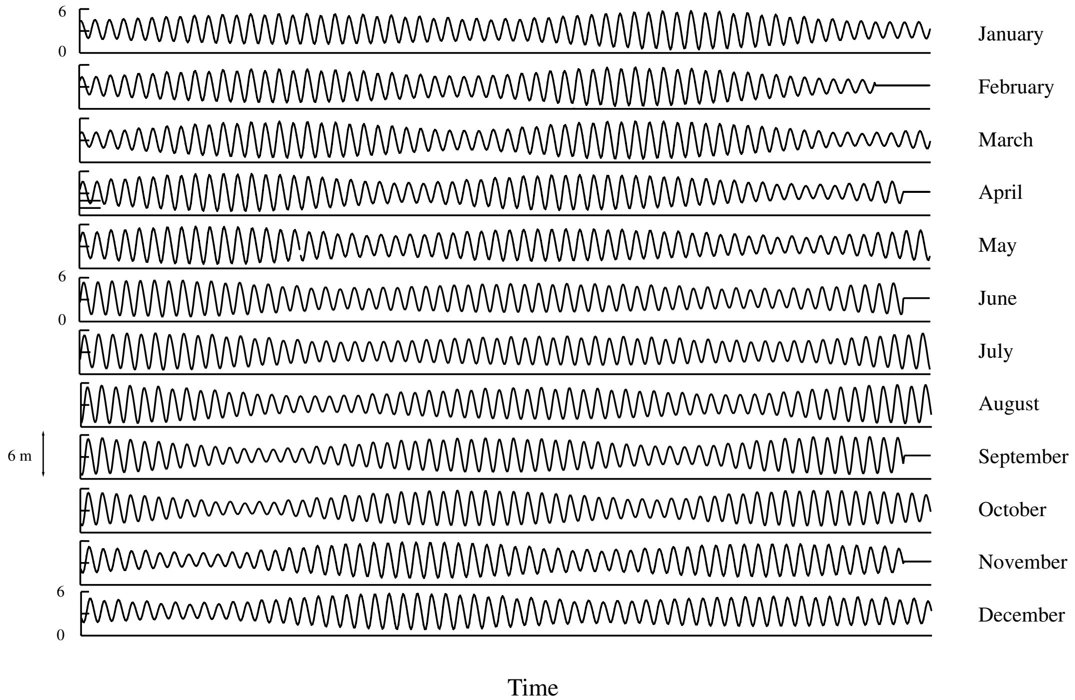

Figure 1.1. A year of sea level observations at Newlyn, southwest Britain, plotted month by month. The dominant semidiurnal tides and the spring–neap changes in range are evident.

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

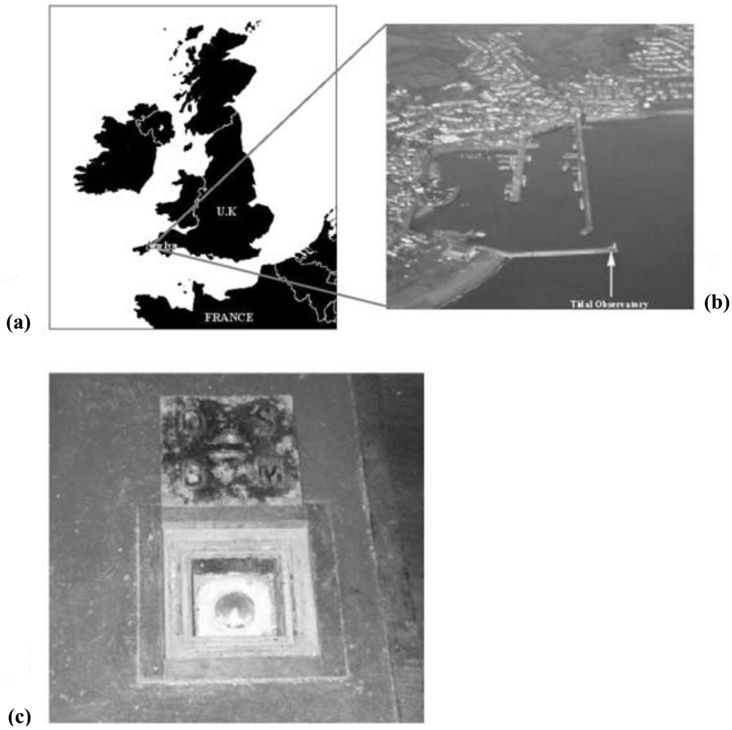

Figure 1.2. The location (a) and harbour details (b) of the Newlyn tide gauge. Newlyn is separated from the Atlantic Ocean by 200 km of shallower continental shelf. The fundamental benchmark for land levelling datum definition in Britain is located alongside the gauge (c).

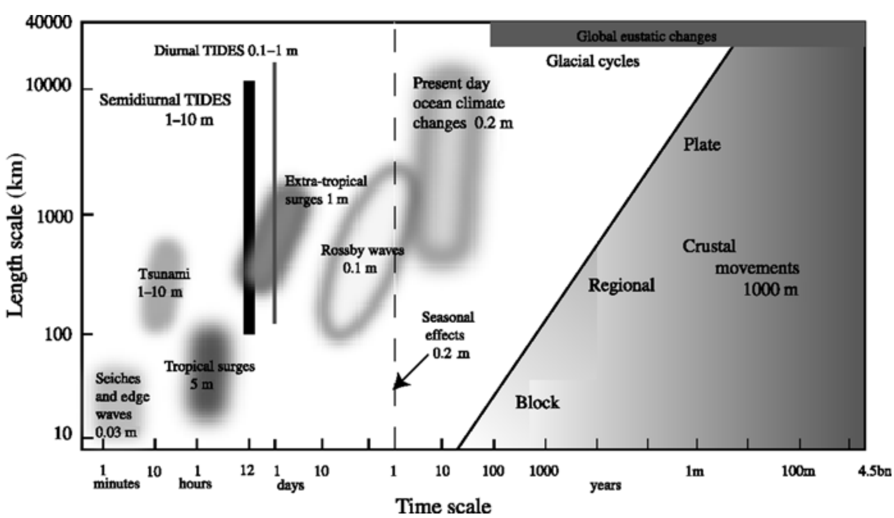

Figure 1.3. A map of the factors that change sea levels in space and time, with typical ranges in metres. Each of the factors discussed in this book occupies a different position on the map. Small-scale rapid changes are in the bottom left-hand corner.

of years. Within this range, sea level records are usually dominated by twice-daily oscillations due to the tides, although there are also seiches, tsunamis, weather effects (surges) and seasonal cycles. The average sea level about which these changes occur is generally called the *mean sea level*. Initially, for some purposes we can consider the mean sea level to be constant, but it does change a little from year to year, and substantially over much longer periods, as we shall show later. We will be looking at all of these processes in more detail, but in the remainder of this section we will describe some of their characteristics as a more general introduction.

For most purposes it is useful to regard the observed sea level as the combined result of three main factors:

$$\text{Observed sea level} = \text{tidal level} + \text{surge level} + \text{mean sea level}$$

These will be considered in turn in this book.

The two main *tidal* features of any sea level record (Figure 1.1) are the *range*, measured as the height between successive high and low levels, and the *period*, the time lapse between one high (or low) level and the next high (or low) level. The tidal responses of the ocean and the responses of the local seas to the forcing of the moon and sun are very complicated, and tidal ranges vary greatly from one site to another.

Nevertheless, in most of the world's oceans the dominant tidal pattern is similar. Each tidal cycle takes an average of almost 12.5 hours, so that two tidal cycles occur for each transit (passage) of the moon through the local longitude. 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 over a fourteen-day period. The maximum ranges, called *spring tides*, occur a day or two after both new and full moons, whereas the minimum ranges called *neap tides*, occur shortly after the times of the first and last lunar quarters. This relationship between tidal ranges and the phase of the moon is due to the additional tide-raising attraction of the sun, which we will discuss in Chapter 2. In Chapter 3 we will develop the idea of adding together several partial tides to represent the observed sea level variations at any particular location, as a tool for tidal analysis and prediction.

In many places, for example at San Francisco on the west coast of the USA, tides with a one-day period, called *diurnal* tides, are similar in magnitude to the local semidiurnal tides. This composite type of tidal regime is called a *mixed* tide. The largest diurnal tides are found in northern Australia and in the Arafura Sea between Australia and New Guinea. Other large diurnal tides are found around Behai Gang in the Gulf of Tongking, China. The dynamics of the ocean response to astronomical tidal forcing, which leads to such a variety of tidal patterns, will be discussed in Chapter 4.

Astronomical forces acting on the major oceans of the world generate and energise the tides. From there the tides spread as waves to the surrounding shallower shelf seas. The tidal ranges on the relatively shallow continental shelves are usually larger than those of the oceans, and it is here that the tides have their biggest impact. Chapter 5 will deal with the behaviour of tides in shallow water and near the coast.

Tidal currents, often called tidal streams, have similar variations. Semidiurnal, diurnal and mixed tidal currents occur, usually having the same characteristics as the local changes in tidal sea levels, but this is not always so. For example, the currents in the Singapore Strait are often diurnal in character while the elevation changes are semidiurnal. The reason for this apparently strange behaviour will be made clearer in Chapter 4. The strongest tidal currents are found in shallow water or through narrow channels that connect two seas, such as the currents through the Straits of Messina between Sicily and the Italian mainland.

The regular and predictable pattern of the tides is slightly (but sometimes spectacularly) altered by the weather, as atmospheric pressure and the winds act on the sea surface. These weather effects (called surges) will be discussed in Chapter 6. Historically, extreme storms have caused many disastrous coastal floods due to the coincidence of large weather-induced surges and large or even moderate high tides. For example, in November 1885, New York was inundated by high sea levels generated by a severe storm that also caused flooding at Boston. More than 6000 people were drowned in September 1900 when the port of Galveston in Texas was overwhelmed by waters that rose more than 4.5 m above the mean high water level, as a result of hurricane winds blowing at more than 50 $m\,s^{-1}$ for several hours. Even these disasters were surpassed by the Bangladesh tragedy of 12 November 1970 when winds raised sea levels by an estimated 9 m. More recently, in October 1999, 10 000 people were killed in Orissa, India, by a 7–8 m surge.

Tsunamis, generated by submarine earthquakes or landslides, are another cause of rare but sometimes catastrophic flooding, particularly for coasts around the Pacific Ocean. Tsunamis are sometimes popularly called 'tidal waves' but this is misleading, because tidal forces do not generate them, nor do they have the periodic character of tidal movements. The naturalist Charles Darwin in *The Voyage Of The Beagle* describes how, shortly after an earthquake on 20 February 1835, a great wave was seen approaching the Chilean town of Concepcion. When it reached the coast it broke along the shore in 'a fearful line of white breakers', tearing up cottages and trees. The water rose to 7 m above the normal maximum tidal level. The largest earthquake of the twentieth century, off southern Chile in 1960, caused huge tsunamis locally and throughout the Pacific Ocean. Tsunamis often set up local oscillations of semi-enclosed sea and basins, called *seiches*, which are also discussed in Chapter 6; more commonly seiches are triggered by winds or internal ocean tides.

Average or *mean sea levels* have generally increased worldwide by about 0.15 m in the past century, due to melting of grounded ice (ice sheets and glaciers) and to the thermal expansion of warming seas. There are local variations: in polar regions sea levels are falling relative to the land, because the land itself is still rising as it recovers from the loading of glaciers thousands of years ago. The local mean sea level at a site is always defined relative to a fixed benchmark, which is protected if possible from movement, to give long-term stability. There is now much popular and scientific interest in how mean sea level will change in this century, in response to enhanced greenhouse global warming; we will return to discuss this in detail in Chapters 7 and 8.

Knowledge of the probability of occurrence of extreme events, as discussed in Chapter 8, is an essential input to the safe design of coastal defences and other marine structures. If mean sea levels increase, extreme sea levels will occur more often. Dramatic extreme sea levels and the resulting coastal flooding are rare events, but there is always a continuous background of sea level changes due to the weather, which raise or lower the observed levels compared with the predicted tidal levels.

1.3 Historical ideas

The link between the moon and tides has been known since very early times. Sailors had a very practical reason 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.

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 massive 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), made systematic measurements and prepared a map of tidal streams in the English Channel. Halley had encouraged Newton, paid for the publication of *Principia* himself and prepared an account of the tides based on Newton's work.

Newton's fundamental understanding has been extended and improved by many other scientists, but it remains the basis for all later developments. Daniel Bernoulli (1700–82) published ideas about an Equilibrium Tide which we shall look at in detail in Chapter 2. 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 in planning safer navigation. Even before the official tables, tidal predictions were published, sometimes based on undisclosed formulae, for example those of the Holden family in northwest England.

Lord Kelvin (1824–1907) showed in detail how tides could be represented as the sum of periodic mathematical terms and designed a machine 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 Coastal Survey of the United States took responsibility for the annual production of official national tide tables for the USA. Soon 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) confirmed the already-known link between higher atmospheric pressures and lower sea levels, known as the inverted barometer effect, by sea level measurements when trapped in the ice during the Arctic winter of 1848–49. Earlier, Ross had helped establish a tide gauge benchmark in Tasmania as a datum 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).

Throughout the twentieth century a series of scientific and technical advances has brought us to the current state of being able to map and model ocean and shelf tides in great detail, using satellite altimeters and the processing power of modern computers. Today one of the highest priorities is to understand and reliably anticipate changes in mean sea level and flood risks, particularly those that may be due to global climate change.

Cambridge University Press
0521532183 - Changing Sea Levels: Effects of Tides, Weather and Climate
David Pugh
Excerpt
More information

Our scientific understanding and our ability to predict future changes depend on the collection of high-quality sea level measurements, made in a variety of ways by different kinds of instruments. In the next section we will consider some of the basic principles on which these instruments operate and some of their individual advantages and disadvantages.

1.4 Measuring sea levels

When measuring sea levels, the aim is to measure the vertical distance between the average surface of the sea and a fixed datum level. We need to smooth out the transient effects of wind waves, which have periods of only a few seconds, to get the averaged sea levels. Measuring sea level is much more difficult than measuring in a laboratory because of difficulties due to waves, corrosion, biofouling, site access, site security and long-term reliability.

Table 1.1 summarises the types of instruments commonly used. These vary from the cheap but inaccurate tide pole, through to dedicated satellite systems. Manuals prepared by the Intergovernmental Oceanographic Commission (1985) of UNESCO give fuller details of how to choose and operate a sea level measuring systems.

When choosing a system it is important to consider the purpose of the measurements. Choices about cost, accuracy, location and duration of measurements follow once this basic purpose is established. Shipping operations may be well served by an accuracy of 0.1 m. For scientific sea level studies, an accuracy of around 0.01 m in individual readings, after wave averaging, is generally possible and acceptable. If the small errors are also random, then averaging over several readings leads to the higher resolution and accuracy that are needed for studying long-term mean sea level trends. For these studies, it is essential to check the gauge zero datum level regularly to ensure that it remains stable. In many cases the cost of good measurements is not much greater than the cost of less accurate systems, once the main structures are paid for. Generally it is best to install the best affordable system, as the data can then serve many different purposes.

1.4.1 Datums

We must emphasise the importance of defining and maintaining a clearly defined and stable zero level or datum for sea level measurements. The datum chosen depends on the application. Those most commonly used are summarised in Table 1.2. The chosen datum may vary from the simple tangible local benchmark at a tide gauge through to the much

Cambridge University Press
0521532183 - Changing Sea Levels: Effects of Tides, Weather and Climate
David Pugh
Excerpt
More information

Table 1.1. *Summary of the characteristics of commonly used methods for measuring sea level.*

Category	Type	Wave averaging	Accuracy	Advantages	Disadvantages
Surface following	Tide pole	By eye	0.02–0.10 m	Inexpensive; easy to make and move; robust	Tedious; needs vertical structure; high maintenance
	Float	Stilling well	0.01–0.05 m		
Fixed sensors	Acoustic reflection	Multiple samples	0.005–0.01 m	Robust; low maintenance; low cost; no vertical structure needed	Needs vertical structure; density and wave corrections, high maintenance
	Radar reflection	Hydrodynamics and multiple samples	0.01 m		
	Pressure				
Remote and mobile	Satellite	Empirical adjustments	0.01 m	Systematic global coverage: high data rate	Expensive: specialist use only; multiple corrections; misses local storms

