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1

Introductory Concepts

1.1 The Nature of Tides

The periodic rise and fall of sea level offers the most visible manifestation of the tides (Figure 1.1). This alternation of high and low waters is of great importance for navigation, coastal safety, and coastal ecology. As a rule, a full cycle of high and low waters takes about half a day; these tides are called *semidiurnal*. However, there are also places with daily periods (*diurnal* tides), and still others where an alternation between the two occurs (*mixed* tides). Figure 1.2 maps the distribution of these periodicities worldwide. The tides are predominantly semidiurnal; diurnal tides occur in isolated patches, such as the Gulf of Mexico, the Caribbean, the Indonesian archipelago, the North Pacific, and around the Pacific Antarctic embayment. In Figure 1.2, the mixed tides are subdivided depending on which of the two – diurnal or semidiurnal – is dominant.

Meanwhile, it is important to realize that the classification of Figure 1.2 offers only a rudimentary distinction, which masks the real complexity of the tidal signal as it is found at any given location. In particular, variations on half-monthly, monthly, and longer timescales are generally present as well. As an aside, we note that the terms "daily" and "monthly" are here to be understood in a loose sense, as an indicative length of time.

Figure 1.2 tells us how often per day high and low waters occur. We now consider their heights, expressed as the *tidal range*: the vertical interval between high and low water levels (Figure 1.3). Again making a rudimentary distinction, we classify the tidal range in three categories: macrotides (ranges exceeding 4 m), mesotides (between 2 and 4 m) and microtides (lower than 2 m). Without exception, macrotides occur in patches that are attached to the continents – an indication that the configuration of the continents acts as one of the organizing principles behind the global pattern of tides.

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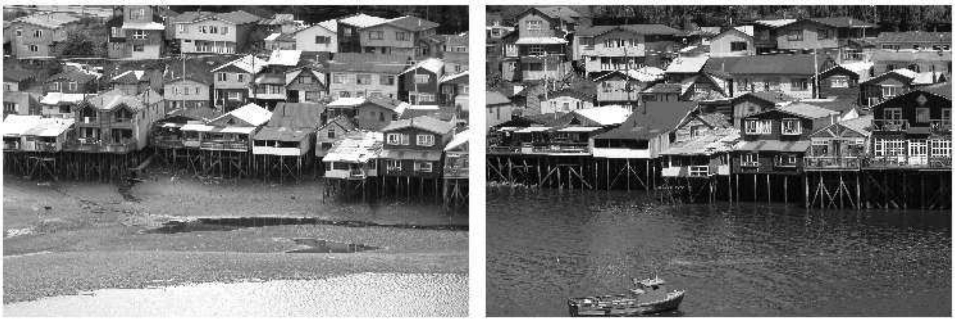

Figure 1.1 View of an embayment in Castro (Chile) during low tides (left) and high tides (right), with the characteristic stilt houses (*palafitos*), designed to be "tideproof." Photographs by the author.

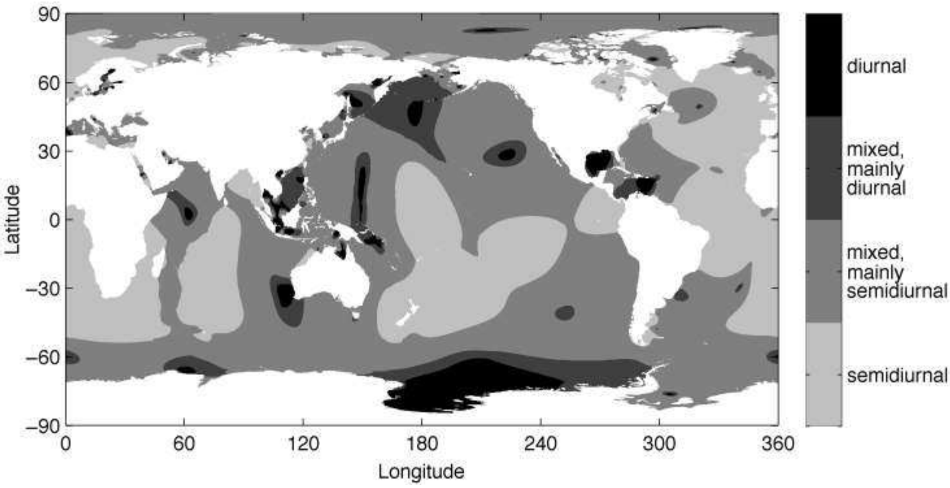

Figure 1.2 Global distribution of semidiurnal, diurnal, and mixed tides. This classification is based on the so-called form factor (to be discussed in Section 4.5), here calculated using data from the global tide model FES2014. This model adopts a data assimilation technique to combine observational data from satellite altimetry and tide gauges with a finite-element numerical tide model. Figure generated using Aviso+ products, courtesy of LEGOS/Noveltis/CNES/CLS.

Figures 1.2 and 1.3 depict the local characteristics of the alternating high and low tides. This way of viewing the tide lies at the basis of tidal predictions, in which a local sea level record is used to predict the moments and heights of future high and low tides at that very location, for example a harbor. The prediction can be made independently of how the tide behaves elsewhere.

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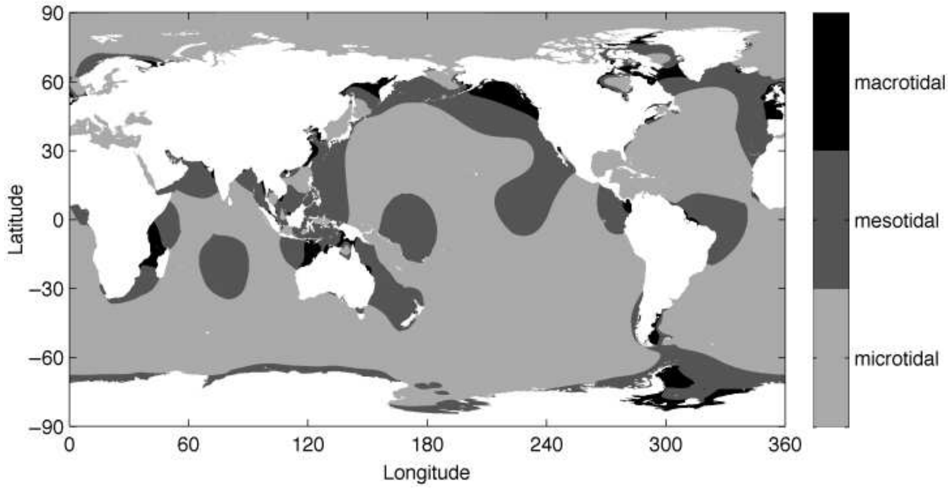

Figure 1.3 Global distribution of the tidal range. Three categories are distinguished: *macrotides:* tidal range > 4 m; *mesotides:* tidal range 2 − 4 m; *microtides:* tidal range < 2 m. The tidal range is here estimated by superposing the (double) amplitudes of the main eight constituents (see Section 4.4 for more details). The amplitudes were obtained from FES2014 model data. Figure generated using Aviso+ products, courtesy of LEGOS/Noveltis/CNES/CLS.

However, from a dynamical perspective, tidal signals at different locations are connected. This can be seen by comparing the moments of high and low tides along a stretch of coastline, as illustrated for the North Sea in Figure 1.4. At a certain point in time, a high tide occurs at the spot marked by a black circle on the east coast of Scotland. Nowhere else along the British North Sea coast do we find a high tide at that same moment. It is only at a distant spot in the southern part of the Netherlands, and then at Denmark, that we find simultaneous high tides. For low tides (gray circles) the spots lie similarly far apart. The distance between locations with simultaneous high (or low) tides typically amounts to several hundred to more than a thousand kilometers. In time, the positions of high and low tides (black and gray circles) propagate along the coast, as loosely indicated by the arrows in Figure 1.4. This presents a glimpse of the tide as a *wave* phenomenon: the high tides being the crests of the wave, the low tides, the troughs. The wavelength, the distance between successive crests, is of the order of hundreds of kilometers or more. This is, anywhere on the globe, much larger than the local water depth; thus, the tide can be classified as a *long wave*. The speed at which high and low tides move along the coast is the phase speed of the tidal wave; it is of the order of 100 kilometers per hour in the example of the North Sea (the phase speed differs per location, though, as it depends on the water depth).

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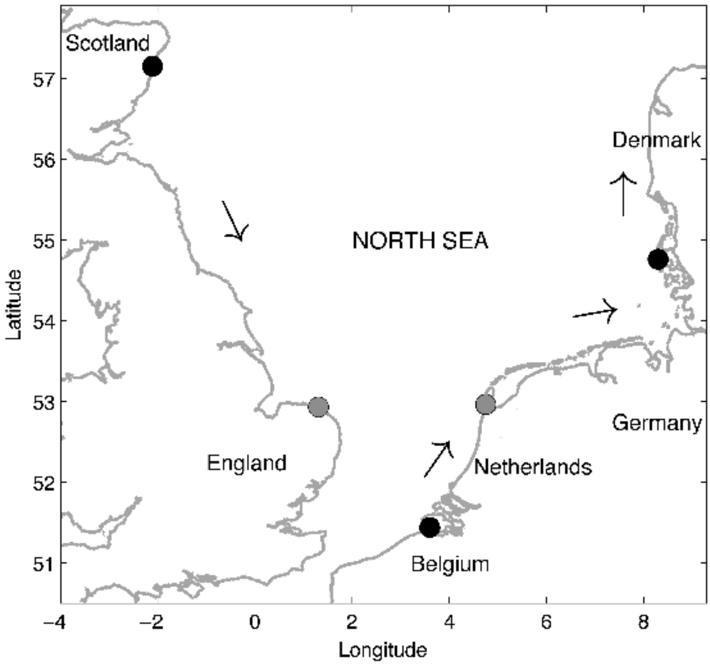

Figure 1.4 A snapshot with locations of high tides (black circles) and low tides (gray circles) along the North Sea coast at a particular instant (based on data from the UK Hydrographic Office). In time, the high and low tides move in a counterclockwise sense along the coast, i.e., southward on the western side and northward on the eastern side of the North Sea, as indicated by the arrows. After one full tidal period, the original situation is replicated.

As with all water waves, a tidal wave as such is an immaterial thing: a signal, an amount of energy that propagates onward. The wave propagation is supported by an oscillatory movement of the water parcels, the *tidal currents*. Tidal currents are of the order of a few centimeters per second in the open ocean, and up to the order of a meter per second in coastal areas. It is important not to confuse the water motion with the wave propagation. In the course of a tidal period, the water particles move for the most part back and forth, while the tidal wave, with its crests and troughs, progresses forward over long stretches. For the water particles, the horizontal distance covered between two successive turnings of the tide is called the *tidal excursion*. It can be expressed as twice the ratio of the tidal current amplitude and the tidal frequency. Its magnitude lies typically in the range of 10–20 km in coastal areas. In the course of a tidal period, particles move back and forth over this distance. In comparison, the vertical movement of the water particles, defined by the tidal range, is much smaller; in other words, the tide plays out primarily in the horizontal. Notice that there is a very clear distinction in scales: the tidal range

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is much smaller than the tidal excursion, which, in turn, is much smaller than the wavelength of the tide.

The relation between tidal currents and sea level is not a straightforward one. Colloquially, the word “ebb” is sometimes used in reference to the phase of the tidal cycle when the sea level drops, but this confounds the water level with the current. In the strict sense of the word, ebb and flood are about the different phases of the tidal *current*: ebb being the current against the direction of tidal wave propagation or out of a tidal basin or estuary, and conversely for flood. Low and high tides sometimes coincide with maximum ebb and flood, sometimes with moments of slack water (i.e., the turning from ebb to flood or vice versa), but often the phase difference lies somewhere in between. The different cases are schematically illustrated in Figure 1.5. The phasing in Figure 1.5a characterizes the tide as a progressive wave, a situation often found along closed coastlines and continents. Figure 1.5b depicts a standing wave, where effectively a superposition occurs between an incident and reflected wave; this situation is sometimes found in tidal basins and estuaries.

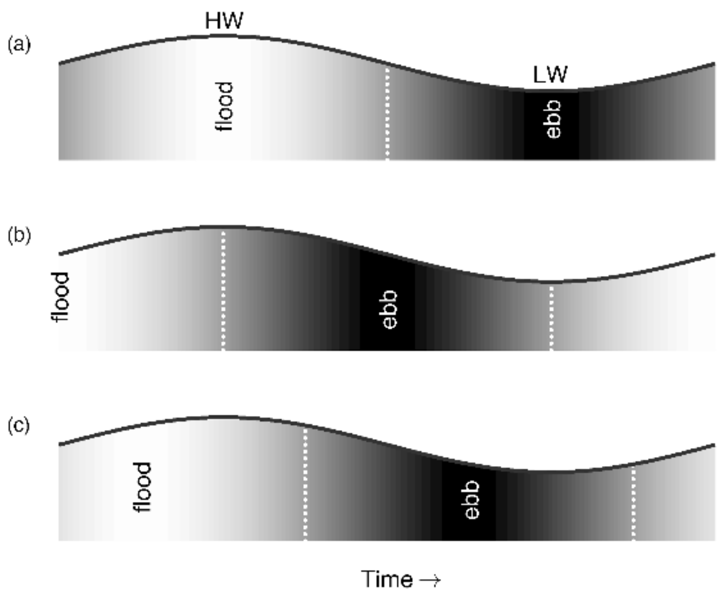

Figure 1.5 A sketch depicting three different scenarios concerning the phase relation between tidal currents and sea level at a given location. The time interval covers one tidal period, with a high water (HW) and a low water (LW). Beneath the surface, the current is depicted, with white and light gray indicating the flood phase, and dark gray to black, the ebb phase. Phases of slack water, i.e., the turnings of the tide, are indicated by vertical dashed lines. In (a), maximum flood coincides with high tide, and maximum ebb with low tide. In (b), slack waters coincide with high and low tides. In (c), we have an intermediate situation.

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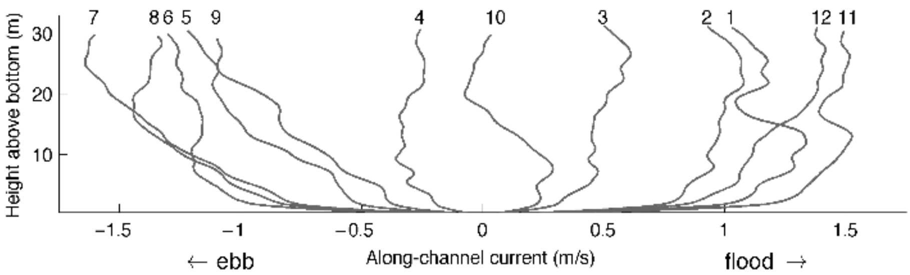

Figure 1.6 Vertical tidal profiles in an inlet, following a tidal cycle. Profiles are numbered according to their temporal sequence; the time interval between them is slightly over an hour, on average. These profiles were obtained from Acoustic Doppler Current Profile (ADCP) measurements at an anchor location, indicated by the black triangle in Figure 1.7. Based on Gerkema et al. (2014).

More often, however, one encounters an intermediate state in those regions, as in Figure 1.5c. Only in the case of Figure 1.5b does the phase of a dropping sea level coincide with ebb, and a rising sea level with flood.

The relation between tidal currents and sea level is further compounded when different periodicities are involved. At some places, one may find a daily signal in sea level variation, whereas ebb and flood occur twice a day – or vice versa.

To add yet another element of complexity to the tidal currents, we should note that the picture sketched so far – of water particles going simply “back and forth” – represents only a special case. In general, tidal currents involve both horizontal directions (west–east and south–north, say), each component with its own phase. In other words, at a moment when the current in one direction vanishes, the other may still be nonzero. In such cases, the notions of ebb, flood, and slack water become blurred.

In coastal regions, the *vertical structure* of tidal currents is an important feature (Figure 1.6). For example, in the tidal exchange in estuaries – with saline water entering during flood and freshwater leaving during ebb – most of the transport takes place in the upper part of the water column, where currents are strongest, which has consequences for the vertical layering of fresh and saline water during the different stages of the tidal cycle (a process called tidal straining).

In coastal regions, another concept closely related to the tidal current is often used, namely the *tidal prism*: the volume of water that flows in and out of a tidal lagoon or basin with flood and ebb. By way of example, values are mapped in Figure 1.7 for a barrier-island system that features a number of inlets. The largest tidal prisms occur in the deepest and broadest inlets.

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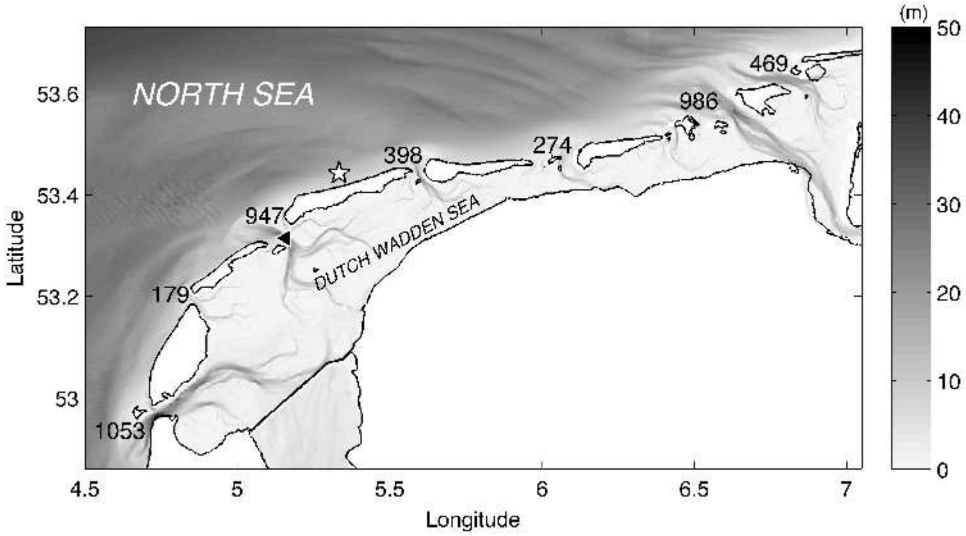

Figure 1.7 Bathymetric map of the western Wadden Sea (cf. Figure 1.4 for geographical orientation), with the tidal prisms indicated at the inlets, in 10^6 m^3; these values are taken from Gräwe et al. (2016). The gray scale shows water depth in meters. Also indicated are the locations of tide gauge *Terschelling Noordzee* (white star), and of *Vlie Inlet* (black triangle) where the current record from Figure 1.6 was obtained. A record from the tide gauge is examined in Section 1.4.

Exercise

1.1.1 At a certain location, a tracer is released during high tide. The tidal excursion is known to be 10 km. How far from the location of release does the tracer move during the following tidal period in the case of Figure 1.5a. And how far in the case of Figure 1.5b?

1.2 Generation and Dissipation of Tides

Semidiurnal and diurnal variations in sea level were already observed and documented in ancient times. In many coastal areas, they were plainly visible. Perceptive observers also noticed a connection with the phases of the Moon (higher tides shortly after full or new Moon). This is mentioned, for instance, by Pliny the Elder in his *Naturalis Historia*, where he also states that the cause of the tides lies in the Moon and Sun. Interestingly, the very idea that the Moon would have any influence on terrestrial affairs (including the tides) was later dismissed by some as a descent into occultism.[1] Others just furnished the cause with a name, as if this amounted to

[1] e.g., Isaac Vossius in his *De motu marium et ventorum* (1663).

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an explanation. This practice was already criticized by Varenius; on the question of what causes the tides, he writes,[2]

> they have no other reply than to say that the Moon pulls the water along by a hidden form of attraction [*sympathiam*]. But these are mere words, which say no more than that the Moon produces the effect in some unknown way. That does not resolve the question.

In Newton's theory, this "hidden form of attraction" is called gravity. In itself, the word does not explain anything, of course; and Newton refrained from speculating about the deeper causes of gravity. The strength of his theory lies elsewhere: 1) the universal nature of the concept of gravity, which at once puts the Moon and Sun on an analogous footing as tide-generating bodies 2) the mathematical formulation of the force of gravity (the inverse-square law), which shifts the focus from the unanswerable *why* to the more productive *how*. In particular, this fundament allows us to derive the expression for the tide-generating force and to examine its implications. Here, we start with a simple qualitative argument that explains why there are predominantly two high and two low waters a day.

1.2.1 Cause of the Tides

We imagine the Earth to be entirely covered with a layer of water (Figure 1.8a). According to Newton's law of gravity, the Earth and Moon exert an attractive force on each other. The first point to note is that the layer of water would stay as it is if the force exerted by the Moon acted equally everywhere on Earth. In other words, *spatial variations* in this force are needed to reshape the layer. These variations are indeed there, since the strength and direction of the force vary; in particular, it becomes weaker at greater distance. Lunar gravity is more strongly felt at position A than at the center of the Earth C (or D and E), since the latter lies farther away from the Moon. The force thus tends to elevate A away from the center C. By the same token, the center C experiences a stronger pull than position B, so that the water at B tends to stay behind, as it were. The upshot is that there is a net force pulling water towards A and C, and away from B and D, as indicated by the arrows in Figure 1.8a.

How the water responds to this force is a different matter altogether. If we assume that the response of the water is immediate, in the sense that the layer always stays adjusted to the force, then it would take the shape depicted in Figure 1.8b. This is the hypothetical *equilibrium tide*. During the daily rotation of the Earth on its axis, one passes two bulges and therefore experiences two high waters.

However, the tides that we experience on Earth look very different; the bulges never really form because they continuously radiate tidal waves, producing a complex pattern of waves in the ocean basins. Moreover, the continents stand in

[2] Varenius in his *Geographia generalis* (1650).

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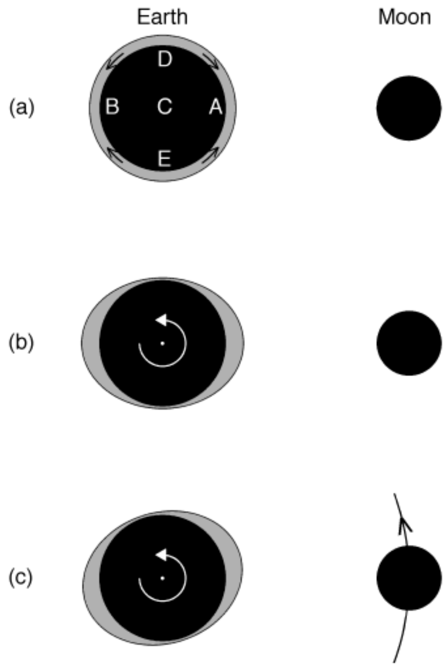

Figure 1.8 Sketches of the Earth and Moon, the former covered by a layer of water (in gray). In (a) we take a layer of uniform depth as a starting point. However, the tide-generating force exerted by the Moon (indicated by arrows) tends to reshape this layer. A hypothetical frictionless and instantaneous response of the water is indicated in (b), with high waters at A and B, and low waters water at D and E. The Earth is seen on top, i.e., the axis of the daily rotation sticks out perpendicularly from the paper, and the sense of rotation is indicated by the white arrow. In the course of a day, i.e., during a full cycle of rotation, one encounters two high waters and two low waters. In (c) the movement of the Moon in its orbit is indicated (note that its sense of revolution is the same as that of the Earth's spin on its axis). Tidal friction now retards the bulges, putting them out of line with the Earth–Moon axis.

their way. However, this does not change the fact that there are two high waters per day, for the tidal waves have the same periodicity as the forcing. The bulges are indeed more about the forcing than about the actual response of the water.

Meanwhile, the key to understanding the origin of tides has been identified: namely, the *spatial variation* in lunar gravity, rather than lunar gravity as such. The same reasoning applies to the tides generated by the Sun's gravitational force.

1.2.2 Moon and Sun

To pursue this last point a little further, we compare the Moon and the Sun with respect to gravity and its derivative. The force of gravity between Moon and Earth (F_m), and between Sun and Earth (F_s) is, respectively,

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$$F_m = G\frac{M_e M_m}{r_m^2}, \qquad F_s = G\frac{M_e M_s}{r_s^2}, \tag{1.1}$$

where G is the gravitational constant, M_e the mass of the Earth, and M_m (M_s) the mass of the Moon (Sun), and $r_{m,s}$ the mutual distance in each case. The values are listed in Table 3.1. We thus find for the ratio of the forces

$$\frac{F_m}{F_s} = \frac{M_m r_s^2}{M_s r_m^2} = 0.0056.$$

The gravitational pull exerted by the Sun is about 180 times stronger than that by the Moon.

Let us now consider the spatial variation of gravity, expressed as the derivative with respect to distance r. This changes the square of r in the denominators of (1.1) into a cubic power, giving more weight to the distance from the Earth, which works in favor of the nearby Moon. Indeed so much so that it reverses the situation:

$$\frac{dF_m/dr}{dF_s/dr} = \frac{M_m r_s^3}{M_s r_m^3} = 2.18.$$

When it comes to tidal generation, the Moon is more weighty than the Sun.

1.2.3 Energy Flows

For centuries, tidal energy has been harvested by humans. This was done already in the late Middle Ages by constructing tide mills that store water during rising tides, which is subsequently released during low tides to drive a wheel. More recently, tidal currents have been exploited in regions with macrotides (Figure 1.3) for the production of electricity. All this constitutes only a minute part of the total tidal energy that is dissipated in the oceans and seas.

Most of the tidal dissipation takes place by friction in the bottom boundary layer of the continental shelf seas. Tidal currents are typically two orders of magnitude stronger in those shallow seas than in the deep ocean. This difference is greatly amplified in the dissipation rate (i.e., friction force times current velocity), which goes with the cubic power of the current.

Before discussing a more detailed picture of tidal dissipation, we turn to the opposite side of the equation: where does the tidal energy come from in the first place? We start by revisiting the imaginary bulges of the equilibrium tide; see Figure 1.8c. Unlike in Figure 1.8b, there is now friction, causing a time lag in the response of the water. The bulges now occur shortly after passing the Earth–Moon axis, as the Earth went on with its daily rotation. This introduces an asymmetry in the setting that has consequences for the Earth as well as for the Moon. The Moon exerts a stronger pull on the bulge facing the Moon than on the opposite one. This

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