11

Tides of the ocean

11.1 Introduction

Anyone who has spent time along the seashore knows that the ocean level changes on an hourly basis. Fishermen plan their activities around high and low tide, such as those who dig clams when tidal flats are uncovered or gather mussels at low tide. Boaters are aware that some channels are only navigable at high tide when waters are deep enough for their boats to pass. Large vessels sailing to port normally enter at slack water or during an ebbing tide. Moving against the tidal flow provides greater steerage for ships than traveling with the currents.

The rise and fall of the tides is one of the major rhythms of Planet Earth. It has a dramatic effect on shoreline processes and coastal landforms. Were it not for the tides there would be no tidal inlets and few natural harbors along the east and Gulf coasts of the United States or along many other barrier coasts of the world. Those familiar with the coast recognize that times of high and low tide occur approximately an hour later each day. More astute observers know that daily tides gradually change in magnitude over the course of a month and that these variations are closely related to phases of the Moon.

Tides are a manifestation of the Moon's and the Sun's force of the gravity acting on the Earth's hydrosphere, as well as the relative orbits of these celestial bodies. Having wavelengths measuring thousands of kilometers, tides are actually shallow-water waves affecting the world's oceans from top to bottom. The surface expression of tides is most dramatic in funnel-shaped embayments, where vertical excursions of the water surface can reach more than 10 m in such areas as the Gulf of Saint-Malo, France (Fig. 11.1) or the Gulf of San Matias, Argentina, and even as high as 15 m in the Bay of Fundy, Canada. Pytheas, a Greek navigator, recorded the Moon's control of the tides in the fourth century BC. However, it was not until Sir Isaac Newton (1642–1727) published his *Philosophiae naturalis principia mathematica* (Philosophy of natural mathematical principles) in 1686 that we finally had a scientific basis for understanding the tides.

Fig. 11.1 Mont Saint Michel in the Gulf of Saint Malo is surrounded by water at high tide due to a 12 m tide that inundates the tidal flats and even floods some of the parking lots.

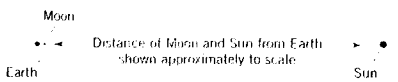
In this chapter we discuss the origin of the tides and how their magnitude is governed by the relative position of the Earth, Moon, and Sun. It will be shown that the complexity of the tides is a function of many factors, including the elliptical orbits of the Earth and the Moon, the declination of the Earth and the Moon, and the presence of continents that partition the oceans into numerous large and small basins. The phenomena of tidal currents and tidal bores are also discussed.

11.2 Tide-generating forces

11.2.1 Gravitational force

As a basis for understanding the Earth's tides, we begin with Newton's universal **law of gravitation**, which states that every particle of mass in the universe is attracted to every other particle of mass. This force of attraction is directly related to the masses of the two bodies and inversely proportional to the square of the distance between them. The law can be stated mathematically as:

$$F = G\frac{M_1M_2}{R^2}$$



	Average distance from Earth	Mass
Moon	385,000 km	7.3×10^{19} t
Sun	149,800,000 km	2×10^{27} t
Sun compared to Moon	390 times further away	27 million times more massive

Newton's Law of Gravitational Attraction (F_g)

$$F_g \sim \frac{\text{mass}}{\text{distance}^2} = \frac{\text{Sun 27 million times more massive}}{(\text{Sun 390 times further away})^2} = 180$$

Tide-producing force (F_t)

$$F_t \sim \frac{\text{mass}}{\text{distance}^3} = \frac{\text{Sun 27 million times more massive}}{(\text{Sun 390 times further away})^3} = 0.46$$

Therefore, the Sun has 46% of the control on tides compared to the Moon

Fig. 11.2 The Earth's tides are primarily controlled by the Moon because in the equation governing the tide-generating force, distance between the masses is cubed. Thus, even though the Sun is much more massive than the Moon, it is also much further away from the Earth than is the Moon.

where F is the force of gravity, G is the gravitational constant, M_1 and M_2 are the masses of the two objects, and R is the distance between the two masses. From the equation it is seen that the force of gravity increases as the mass of the objects increases and as the objects move closer together. Distance is particularly critical because this factor is squared (R^2) in the equation. Thus, the celestial bodies producing the Earth's tides are the Moon, due to its proximity, and the Sun, because of its tremendous mass. The other planets in the Solar System have essentially no effect on the tides due to their relatively small mass as compared to the Sun and their far distance from Earth as compared to the Moon. Although the attractive forces of the Moon and Sun produce slight tides within the solid Earth and large oscillations in the atmosphere, it is the easily deformed liquid Earth (hydrosphere) where tides are most clearly visible.

As illustrated in Fig. 11.2, the Sun is 27 million times more massive than the Moon, but at the same time it is 390 times further away. After substituting the respective mass and distance values for the Moon and Sun into Newton's gravitation equation, it can be seen that the attractive force of the Sun is approximately 180 times greater than that of the Moon. However, we still know that the Moon has a greater control on the Earth's tides than does the Sun.

11.2.2 Centrifugal force

To understand how the gravitational force actually produces the tides it is necessary to learn more about orbiting celestial bodies, including the Moon–Earth system and the Earth–Sun system. First, it is important to recognize that counteracting the gravitational attraction between the Moon and Earth is the centrifugal force (Fig. 11.3). Centrifugal force is a force that is exerted on all objects moving in curved paths, such as a car moving through a sharp right bend in the road. The centrifugal force is directed outward and can be felt by the car's driver as he or she is pressed against the car door through the turn. Likewise, the centrifugal force balances the attractive force between the Earth and the Moon. If the Moon were stopped in its orbit, the centrifugal force would disappear and gravitational force would cause the Earth and the Moon to collide. Conversely, if the gravitational force ceased between the two bodies, the Moon would career into space.

Thus far, we have been careful not to say that the Moon orbits the Earth. In fact, the Earth and the Moon form a single system in which the two bodies

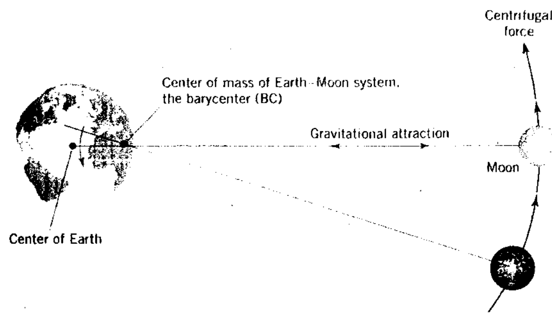


Fig. 11.3 The Earth–Moon system rotates around a common center of mass called the barycenter, which is within the Earth. The gravitational attraction between the Earth and the Moon is balanced by the centrifugal force.

revolve around a single center of mass. Because the Earth contains approximately 81.5 times more mass than the Moon, the center of mass of the system, called the barycenter, is within the Earth. The barycenter can be determined from knowledge that the average distance between the center of the Earth and the center of the Moon is 385,000 km. The center of mass must be 81.5 times closer to the Earth's center than to the Moon's. By dividing 385,000 by 81.5 we calculate that the center of mass is 4724 km from the Earth's center. The Earth's radius is 6380 km and therefore the center of the Earth–Moon system is located 1656 km (6380 − 4724) beneath the surface of the Earth. The Earth–Moon system can be visualized by considering a dumbbell with a much larger ball at one end (81.5 times more massive) than the other. If this dumbbell were thrown end over end, it would appear as though the large ball (the Earth) wobbled and the small ball (the Moon) orbited the large ball.

It should be understood that because the entire Earth is revolving around the center of the Earth–Moon system, every unit mass on the surface of the Earth is moving through an orbit with the same dimensions. The average radius of the orbits is 4724 km. The movement of the Earth around the Earth–Moon center of mass should not be confused with the Earth spinning on its axis, which is a separate phenomenon. Thus, if every unit mass on the surface of the Earth has the same size orbit, then it follows that the centrifugal force of the unit masses must also be equal.

11.2.3 Tide-producing force

Ocean tides exist because gravitational and centrifugal forces are unequal on the Earth's surface (hydrosphere) (Fig. 11.4). In fact, the gravitational attraction between the Moon and Earth only equals the centrifugal force of the Earth at the center of their two masses, which is determined to be 1656 km inside the Earth's surface. Thus, if we consider a unit mass at the surface of the Earth at a site facing the Moon, this mass experiences a force of attraction by the Moon that is greater than the counterbalancing centrifugal force. The larger gravitational force

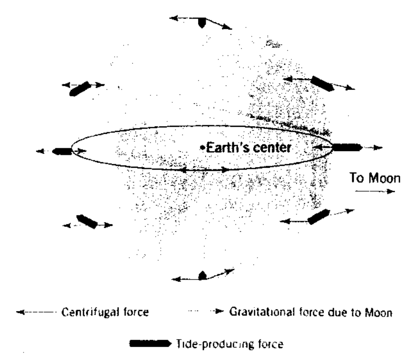


Fig. 11.4 Tides are generated in the Earth's hydrosphere due to differences between the centrifugal force and the Moon's attractive force.

is explained by the fact that at this location the distance to the Moon is less than the distance between the center of masses and the Moon, where the two forces are equal. Remember in Newton's gravitation equation that as distance decreases, the force of gravity increases. Conversely, for a unit mass on the opposite side of the Earth the centrifugal force exceeds the gravitational attraction exerted by the Moon because this site is farther away from the Moon than the center of mass, where the forces balance. Thus, the unequal forces on either side of the Earth cause the hydrosphere to be drawn toward the Moon on the near side of the Earth and to be directed away from the Moon on the opposite side. This produces two tidal bulges of equal size that are oriented toward and away from the Moon. These forces also result in depressions in the hydrosphere that are located halfway between the two bulges on either side of the Earth. If we disregard the curvature of the Earth, the tides can be thought of as a long wave, with the crest being the bulge and the depression being the trough. This waveform is called the tidal wave, which should not be confused with a tsunami, which sometimes is inappropriately referred to as a tidal wave.

The above description reveals that forces generating the Earth's tides are very sensitive to distance. The tide-generating force is derived by calculating the difference between the gravitational force and the centrifugal force. A simplified form of the relationship is given by:

$$F \approx \frac{M_1 M_2}{R^3}$$

The tide-generating force F is proportional to the masses M_1 and M_2 and inversely related to the cube of the distance between the bodies R^3. When these computations are performed for unit masses over the surface of the Earth, it is seen that the resulting vectors are oriented toward and away from the Moon (Fig. 11.4). Note also that **distance** is cubed in the equation, which explains why the Moon exerts a greater control on the Earth's tides than does the Sun. As illustrated in Fig. 11.2, after substituting the respective mass and distance values into the above equation, it is calculated that the tide-generating force of the Sun is only 46% of that of the Moon.

11.3 Equilibrium tide

The equilibrium tide is a simplified model of how tides behave over the surface of the Earth given the following assumptions:

1 The Earth's surface is completely enveloped with water, with no intervening continents of other landmasses.

2 The oceans are extremely deep and uniform in depth, such that the seafloor offers no frictional resistance to movement of the overlying ocean water.

3 There are two tidal bulges that remain fixed toward and away from the Moon.

11.3.1 Tidal cycle

In our initial discussion of the equilibrium tide model we will neglect the effects of the Sun; they are treated below. If we consider a stationary Moon, then the Earth passes under the two tidal bulges each time it completes a rotation around its axis (Fig. 11.5). In this idealized case the wavelength of the tidal wave, which is the distance between the tidal bulges, would be half the circumference of the Earth. High tide coincides with the Earth's position under the bulges and low tide corresponds to the troughs located midway between the bulges. The tidal period would be 12 hours (interval between successive tidal bulges). The rhythm of tidal changes referred to as the tidal cycle can be better conceptualized if we choose a position on the equator directly facing the Moon and record how the water level fluctuates at this site through time as the Earth spins on its axis. At 12:00 midnight the ocean is at high tide because the Earth is directly under the maximum extent of the tidal bulge. After high tide the water level gradually drops, reaching low tide six hours later at 6:00 a.m. During the next six hours the tide rises, attaining a second high tide at 12:00 noon. The cycle repeats itself over the next 12 hours.

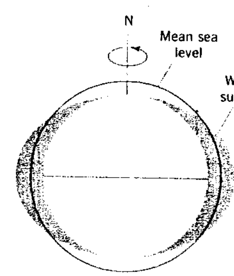


Fig. 11.5 Under idealized equilibrium tide conditions the Earth passes beneath two equal and opposite tidal bulges every 24 hours. This situation assumes an absence of continents, a uniform depth ocean, and the moon aligned with the equator.

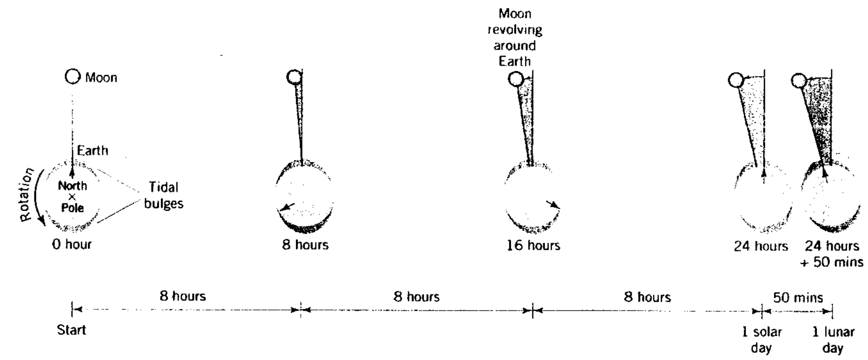


Fig. 11.6 Cartoon illustrating why times of high and low tide occur 50 minutes later each successive day.

11.3.2 Orbiting moon

In the real world the Moon is not stationary but it completes an orbit around the center of the Earth–Moon system in a period of 27.3 days. The Moon moves in the same direction as the Earth spins on its axis and therefore after the Earth completes a full 24 hour rotation the Moon has traveled 13.2° of its orbit. For the Earth to "catch up" to the Moon, it must continue to rotate for an additional 50 minutes. Thus the Moon makes successive transits above a given location on the Earth in a period of 24 hours and 50 minutes, which is called the lunar day (Fig. 11.6). Because the Moon is moving, high and low tides do not take place every 12 hours as discussed in the simple model above, but every 12 hours and 25 minutes. The time interval between high and low tide is about 6 hours and 13 minutes. When there are two cycles in a day (actually 24 hours and 50 minutes) they are called semi-diurnal tides.

11.3.3 The Moon's declination

So far in our discussion of the tides, we have simplified matters by envisioning a Moon that is always directly overhead of the equator. However, the Moon's orbit is actually inclined to the plane containing the equator. Over a period of a month the Moon migrates from a maximum position 28.5° north of the equator to a position 28.5° south of the equator and back again. When the Moon is directly overhead of the tropics the tides are called **tropic tides** and when it is over the equator they are called **equatorial tides**. Because the Moon is the dominant controller of the tides it follows that when the Moon is positioned far north or south of the equator the tidal bulges will also be centered in the tropics. This arrangement of the tidal bulges leads to a semidiurnal tidal inequality, meaning that successive tides have very different tidal ranges (tidal range is

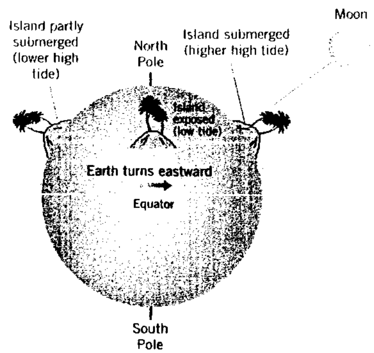


Fig. 11.7 In its orbit around the Earth, the Moon moves above and below the equator. When the Moon is not aligned with the equator, successive tidal bulges and the corresponding tidal ranges are unequal. This phenomenon is called a semi-diurnal inequality.

the vertical difference in elevation between low and high tide). For example, if you are along the east coast of Florida at tropic tide conditions, during one tidal cycle the tide will come up very high and then go out very far, generating a relatively large tidal range. During the next tidal cycle, a low high tide is followed by a high low tide, producing a small tidal range. As seen in Fig. 11.7, the diurnal inequality is explained by the fact that when the tidal bulges are asymmetrically distributed about the equator, the Earth will rotate under very different sized tidal bulges. This translates to unequal successive high and low tides. It should be noted that during equatorial tide conditions there is little to no inequality of the semi-diurnal tides, whereas they reach a maximum during tropic tides.

11.4 Interaction of the Sun and the Moon

It was shown above that the Sun's tide-generating force is a little less than half that of the Moon (46%). It is important to note that, just like the Moon, the Sun produces bulges and depressions in the Earth's hydrosphere. These are called solar tides and they have a period of 12 hours, unlike the 12 hours and 25 minutes period of the lunar tides. The period is 12 hours because the Earth passes through two solar bulges every day (24 hours). One way of explaining the interaction of the Moon and Sun is to show how the Sun enhances or retards the Moon's tide-generating force. In order to do this we must first understand how the phases of the Moon correlate with the position of the Earth, the Moon, and the Sun.

New Moons and full Moons result when the Earth, the Moon, and the Sun are aligned, a condition referred to as **syzygy** (a great Scrabble word worth many points). A new Moon occurs when the Moon is positioned between the Earth and the Sun, whereas a full Moon results when the Moon and the Sun are on the opposite sides of the Earth. When the Moon forms a right angle with the Earth and the Sun (**quadratic** position), only half of the Moon's hemisphere is illuminated. This phase occurs during the Moon's first and third quarters. The Moon cycles through these different phases over a period of 29.5 days.

During new and full Moons when the Earth, the Moon, and the Sun are all aligned, the tide-generating forces of the Moon and the Sun act in the same direction and the forces are additive (Fig. 11.8). Conceptually, one can envision the Sun's bulge sitting on top of the Moon's bulge. Between the bulges the Sun's trough further depresses the Moon's trough. The double bulges and double troughs lead to very high high tides and very low low tides. This condition is called a spring tide and is characterized by maximum tidal range (Fig. 11.9).

During quadratic conditions the Sun's effects are subtractive from the Moon's tide-generating force. Because the Moon is positioned at 90° to the Earth and the Sun, its bulge coincides with the Sun's trough and its trough is positioned at the Sun's bulge. The superposition of bulges and troughs causes destructive interference and produces low high tides and high low tides. This condition is called a neap tide and is characterized by minimum tidal ranges (Fig. 11.9). When the Earth, Moon, and Sun are arranged in positions between syzygy and quadratic we experience mean tides with average tidal ranges.

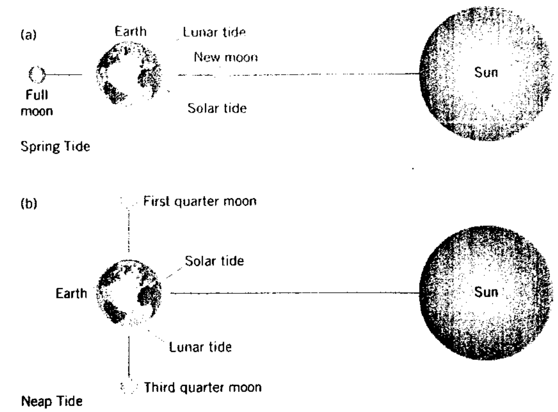


Fig. 11.8 The alignment of the Earth, Moon, and Sun determines the size of the tidal bulges and the magnitude of the tidal range. (a) During periods of full and new moons the tidal bulges are additive, producing relatively large tidal ranges. (b) When the Moon, Earth, and Sun are at right angles during half moon conditions the tidal forces are subtractive and tidal ranges are relatively small.

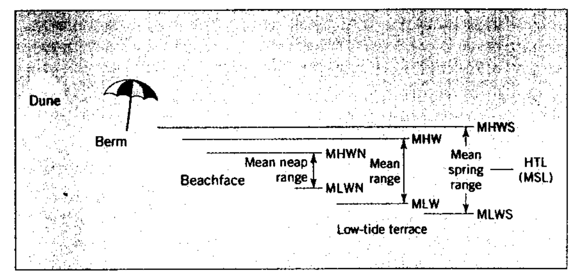


Fig. 11.9 Tidal ranges and the elevation of high and low tides are a function of the position of the Earth, Moon, and Sun.

Spring and neap tides occur approximately every 14 days, whereas mean tides occur every seven days.

11.5 Effects of orbital geometry

Remembering that the tide-producing force is particularly sensitive to distance, it is understandable that the geometry of both the Earth's and the Moon's orbits affects the tides. The Earth revolves around the Sun in an elliptical orbit and the Sun is situated at one of the foci of the ellipse. In early January the Earth is nearest to the Sun, at a position called perihelion (Fig. 11.10). Six months later (July) the Earth is at aphelion, furthest from the Sun. The difference in distances is approximately 4%. The Moon's orbit around the center of the Earth–Moon system is also elliptical. When the Moon is close to the Earth the position is referred to as perigee and when it is most distant it is called apogee. There is a 13% difference between perigee and apogee.

If we consider all the various factors that influence the magnitude of the tides, we begin to understand why tidal ranges and high and low tidal elevations change on a daily basis. Tide levels are especially important during storms. In early February 1978 a major northeast storm, named the Blizzard of 1978, wreaked havoc in New England, dropping over two feet of snow and completely immobilizing the residents for several days. The Blizzard of 1978 was

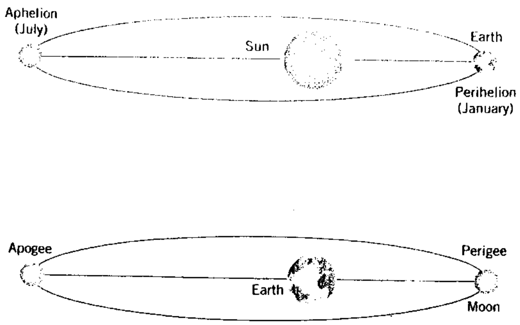


Fig. 11.10 The elliptical orbit of Earth affects its distance from the Sun and therefore the magnitude of the tide-producing force during the year.

a particularly menacing storm causing widespread beach erosion, the destruction of hundreds of coastal dwellings, and hundreds of millions of dollars worth of damage to roadways and other infrastructure. One of the reasons why this storm was so severe was the astronomic conditions that existed at the time of the storm. The Earth, Moon, and Sun were in syzygy so the storm hit during spring tide conditions. At the same time the Moon was at perigee and the Earth and Sun were close to a perihelion position. Syzygy, perigee, and perihelion combined to raise high tide levels 0.55 m above normal. The extreme astronomic tides coupled with the 1.4 m storm surge caused extensive flooding. Storm waves elevated by high water levels broke directly against foredune ridges, across barriers, and over seawalls. Had the storm hit during quadratic, apogean, and aphelion conditions, high tide waters would have been 1.1 m below the February Blizzard levels and damage would have been an order of magnitude less (Fig. 11.11).

11.6 Effects of partitioning oceans

We have been treating tides as if the Earth were completely enveloped by a uniformly deep ocean. However, we know that continents and island archipelagoes have partitioned the hydrosphere into several interconnected large and small ocean basins whose margins are generally irregular and quite shallow. Because oceans do not cover the surface of the Earth, the tidal bulges do not behave as simplistically as has been presented thus far. In addition to the complexities imparted by the presence of landmasses, the equilibrium tide concept is further complicated by the fact that the Earth spins faster in lower latitudes and slower in higher latitudes than the tidal wave. Thus, the oceans do not have time to establish a true equilibrium tide. Finally, the ocean tides are affected by the Coriolis effect, which is generated by the Earth's rotation. This causes moving objects, including water masses, to be deflected to the right in the northern hemisphere and to left in the southern hemisphere. For example, the Gulf

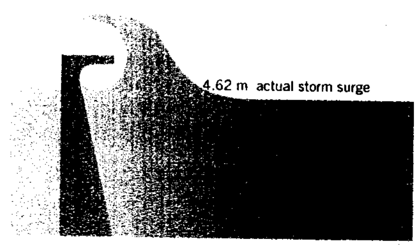


Fig. 11.11 Cartoon of seawall along Winthrop Beach, Massachusetts that was overtopped by storm waves during the blizzard of 1978. Note that if the storm had occurred during low astronomic tidal range conditions, fewer waves would have broken over the seawall and the overall damage to the New England shoreline would have been far less severe.

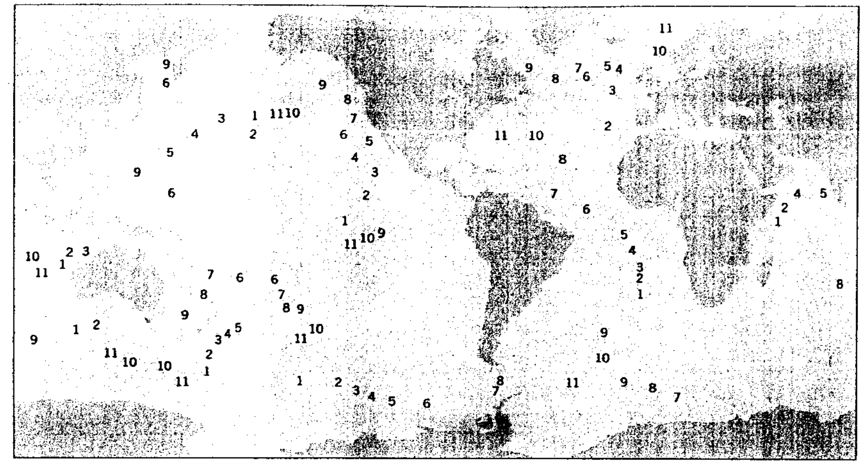


Fig. 11.12 Amphidromic systems throughout the world's oceans. The tidal wave rotates in a counterclockwise direction around amphidromic points in the northern hemisphere and in a clockwise direction in the southern hemisphere. The lines radiating from the amphidromic points are co-tidal lines. They indicate hypothetical times in which the crest of the tidal wave passes through the ocean basins.

Stream that flows northward along the margin of North America is deflected northeastward toward Europe due to the Coriolis effect.

In the dynamic model of ocean tides we no longer envision static ocean bulges that remain fixed toward the Moon and under which the Earth spins; instead, the tidal bulges rotate around numerous centers throughout the world's oceans (Fig. 11.12). An individual cell is called an amphidromic system and the center of the cell around which the tidal wave rotates is known as the amphidromic point or nodal point. The rotation of the tidal wave is due to the Coriolis effect and is counterclockwise in the northern hemisphere and clockwise in the southern hemisphere.

To understand the behavior of an amphidromic system let us first begin with a hypothetical square-shaped ocean basin that responds to the Moon's tide-generating forces (Fig. 11.13). The tidal wave that develops under these conditions exhibits elements of both a standing wave and a progressive wave. As the Earth spins and the Moon travels from east to west over the hypothetical basin, the tidal bulge sloshes against the western side of the basin in an attempt to keep abreast of the passing Moon. As the Earth continues to rotate, the bulge of water begins to flow eastward back toward the low center of the basin. However, the Coriolis effect deflects this water mass to the southern margin of the basin, and water piles up there. This in turn creates a water surface that slopes northward and the process is repeated. The end result is a tidal wave that rotates in a counterclockwise direction around the basin with a period of 12 hours and 25 minutes. High tide is coincident with the tidal bulge and low tide occurs when the bulge is along the opposite side of the basin.

When a line is drawn along the crest of the tidal wave every hour for a complete rotation, the resulting diagram looks like a wheel with spokes. It depicts how the tidal wave rotates within the hypothetical basin and its center is the amphidromic point. The spokes are called co-tidal lines and they define points within the basin where high tide (and low

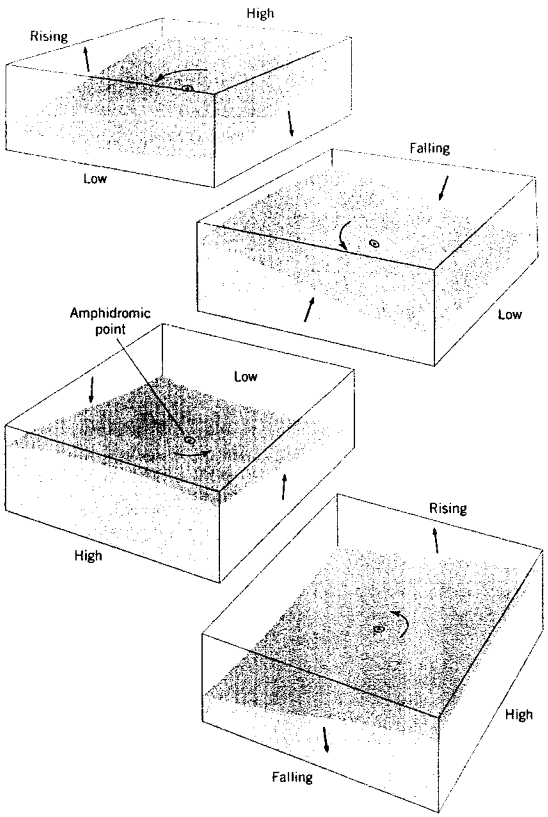


Fig. 11.13 Hypothetical tidal wave rotating around an amphidromic point in a square-shaped basin. Note that water elevation changes (tidal range) increase outward from the amphidromic point. The Coriolis effect causes rotation of the tidal wave.

tide) occurs at the same time (Fig. 11.12). If points of equal tidal range are contoured within the basin a series of semi-concentric circles are formed around the amphidromic point. These contours with equal tidal range are referred to as co-range lines. Ideally, tidal range is zero at the amphidromic point and gradually reaches a maximum toward the edge of the basin. Due to the land barriers and other factors the world's oceans are divided into approximately 15 amphidromic systems. This does not include smaller seas that have their own amphidromic cells, such as the Gulf of Mexico (one system), Gulf of Saint Lawrence (one system), and North Sea (three systems).

11.7 Tidal signatures

In the ideal case, we expect two tidal cycles daily (actually 24 hours and 50 minutes). However, the highly variable basinal geometries of the world's ocean and modifications of the tidal wave as it

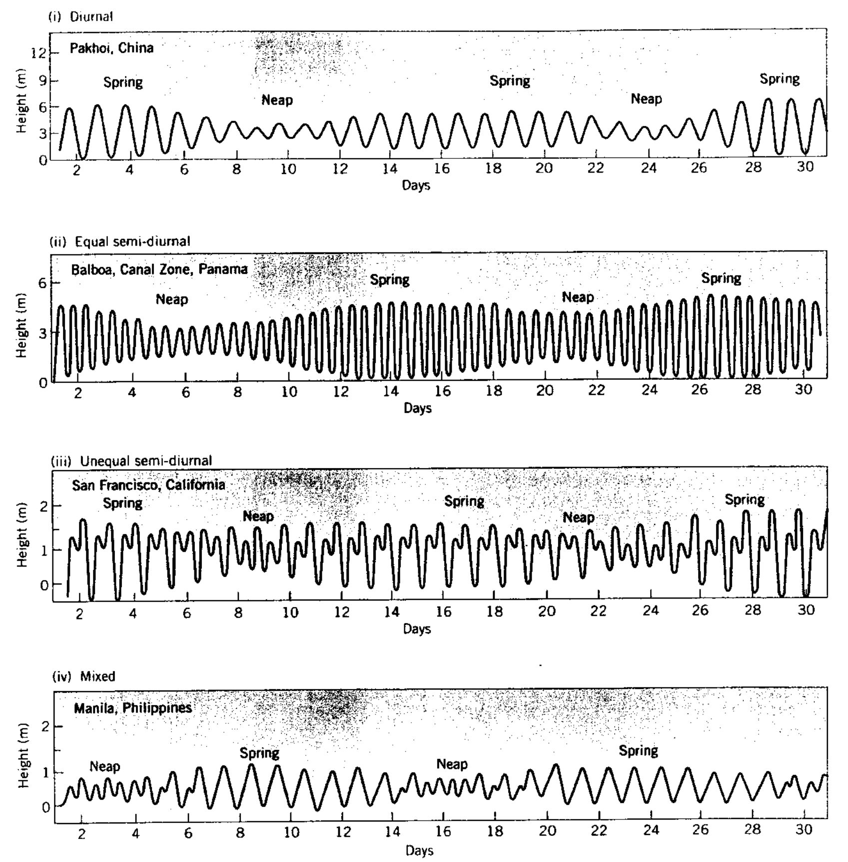
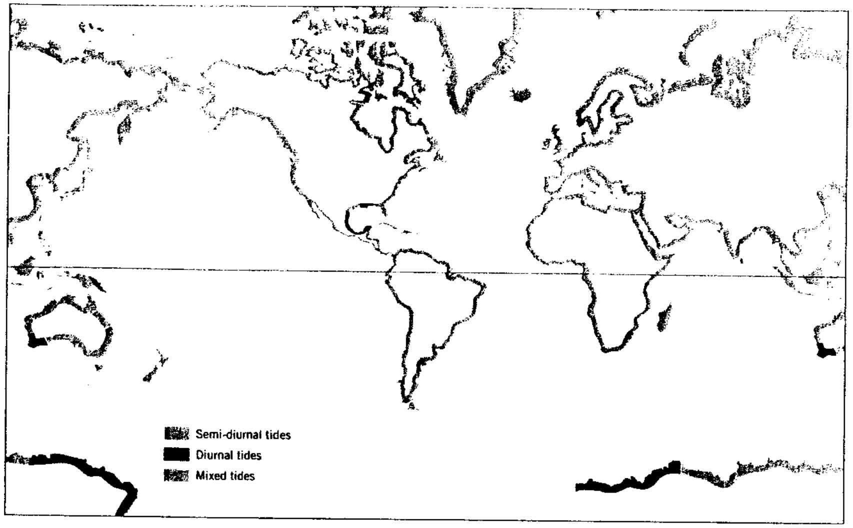


Fig. 11.14 Coastlines throughout the world experience a variety of tidal signatures. (a) The major types include: (I) diurnal tides, one tide daily; (II) semi-diurnal tides, two tides daily; (III) semi-diurnal tides with strong inequality; (IV) mixed tides, combination of diurnal and semi-diurnal tides. (From R. A. Davis, 1977, *Principles of Oceanography*, 2nd edn. Reading, MA: Addison-Wesley, p. 155, Fig. 8.9.)

shoals across the continental shelf, as well as other factors, have combined to produce a variety of tidal signatures throughout the world's coastlines. There are three major types of tides (Fig. 11.14):

1 Diurnal tides. Coasts with diurnal tides experience one tidal cycle daily, with a single high and low tide. They have a period of 24 hours and 50 minutes. This type of tide is rare and commonly associated with restricted ocean basins, including certain areas within the Gulf of Mexico, the Gulf of Tonkin along Southeast Asia, and the Bering Sea. In these areas distortions of the tidal wave produce



(b)

Fig. 11.14 (*cont'd*) (b) Geographic distribution of tidal types.

a natural tidal oscillation coinciding with 24 hours and 50 minutes. The open southwest coast of Australia is an exception to this general trend.

2 Semi-diurnal tides. This is the most common type of tide along the world's coast. Semi-diurnal tides are characterized by two tidal cycles daily with a period of 12 hours and 25 minutes. Seldom, however, are the two tides of the same magnitude except when the Moon is over the equator or at locations near the equator. As discussed above, when the Moon is over the tropics successive tidal bulges (the tidal wave) have unequal magnitudes, producing different tidal ranges with high and low tides reaching different elevations. This condition of unequal tides is called a semi-diurnal inequality.

3 Mixed tides. This type of tide occurs extensively throughout the world. As the name implies mixed tides have elements of both diurnal and semi-diurnal tides. The signature varies during a lunar cycle from a dominant semi-diurnal tide with a small inequality to one that exhibits a very pronounced inequality. At some sites, including San Francisco, Seattle, and Port Adelaide in Australia, during part of the lunar month one of the two daily tides manifests itself as a very small vertical excursion measuring no more than 0.1–0.3 m. These tides have a distinct diurnal signature. Along other coasts, such as Los Angeles, Honolulu, and Manila in the Philippines, the second daily tide essentially disappears and the tide becomes totally diurnal.

Thus, the complexities that produce and modify the Earth's tides are revealed by the variability in their tidal signature throughout the world and even temporally as viewed during a lunar cycle.

11.8 Tides in shallow water

11.8.1 Continental shelf effects

In the middle of the ocean the tidal wave travels with a speed of 700 km h^{-1}. In these regions the

tidal range is only about 0.5 m. The tidal wave that reaches the coast travels from the deep open ocean across the continental margin to the shallow inner continental shelf. Similar to wind-generated waves, shoaling of the tidal wave along this pathway causes it to slow down. The tidal wave that traverses the entire continental margin is reduced in speed to about 10–20 km h^{-1}. Like wind waves, the tidal waves also steepen, which is reflected in an increase in tidal range. For example, the tidal wave in the north Atlantic is estimated to be 0.8 m in height (tidal range) at the edge of the continental shelf. The wave steepens as it propagates through the Gulf of Maine, producing a tidal range of 2.7 m along the coast of Maine. On a worldwide basis, using an average shelf width of 75 km, it is estimated that the tidal wave will heighten from 0.5 m in the deep ocean to about 2.4 m along the coast after it traverses the continental shelf. Variations from this value are due to differences in shelf width and slope, and variability in the configuration of the coast. It is of interest to note that along the east coast of the United States, the continental shelf is relatively wide off the Georgia coast, where tidal ranges reach 2.6 m. North and south of this region the shelf narrows and tidal ranges correspondingly reduce to 1.1 m at Cape Hatteras and less than a meter along central Florida (Fig. 11.15).

Fig. 11.15 Tidal range along the East coast of the United States is controlled in part by the width of the continental shelf. As the tidal wave travels from the deep ocean across the shallow continental shelf, its speed slows and its crest steepens. The amount of wave steepening, which increases the tidal range, is proportional to the length and gradient of the shelf. Thus, the wide, gentle shelf off the Georgia coast produces a tidal range greater than 2 m, whereas the steep narrow shelves bordering south Florida and Cape Hatteras in North Carolina generate tidal ranges less than 1 m. (From D. Nummedal, G. Oertel, D. K. Hubbard & A. Hine, 1977, Tidal inlet variability – Cape Hatteras to Cape Canaveral. In *Proceedings of Coastal Sediments '77*. Charleston, SC: ASCE, pp. 543–62.)

11.8.2 Coriolis effect

Just as the Coriolis effect produces a counterclockwise rotation of the tidal wave in large amphidromic systems in the northern hemisphere, it also influences the propagation of the tidal wave into gulfs and seas from the open ocean. This phenomenon is demonstrated well in the North Sea, where the Coriolis effect dramatically modifies tidal ranges. The North Sea is a shallow (<200 m), rectangular-shaped basin approximately 850 km long from the Shetland Islands southeastward to the German Friesian Islands and 600 km wide from Great Britain eastward to Jutland in Denmark. Tides in the North Sea are forced by the North Atlantic amphidromic system (Fig. 11.12). The tidal wave approaches through the northern open boundary of the North Sea and propagates southward. Ultimately, the wave partially reflects off the southern margin of the basin and interacts with the next incoming wave. The resulting oscillations combined with the Coriolis effect produce three amphidromic systems, two of which are displaced toward the coasts of Norway

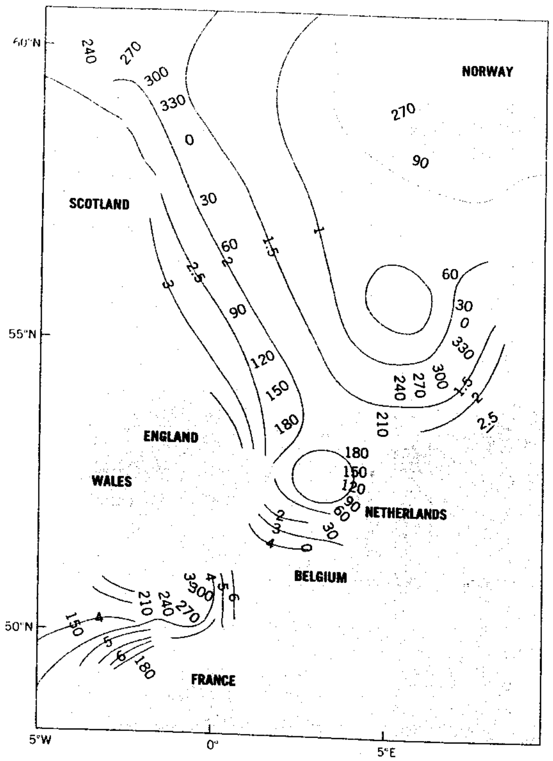


Fig. 11.16 The distribution of tidal ranges in the North Sea illustrates how the Coriolis effect affects tidal wave propagation into a shallow sea. (From D. A. Huntley, 1980, Tides on the north-west European continental shelf. In F. T. Banner, M. B. Collins & K. S. Massie (eds), *The North-West European Shelf Seas: The Sea Bed and the Sea in Motion. II Physical and Chemical Oceanography and Physical Resources*. Amsterdam: Elsevier.)

and Denmark. As illustrated by the co-range lines in Fig. 11.16, tidal ranges are much higher along the east coasts of England and Scotland (~4 m) than on the Norwegian and Danish coasts (<1 m). This disparity is caused by the tidal wave being deflected to the right as it moves into the North Sea. Water is piled up on the western side of the basin and diminishes the tidal ranges along the eastern side.

A similar situation occurs in the English Channel. Here the tidal wave approaches from the southwest and propagates eastward through the channel. The Coriolis effect deflects water away from the English side of the channel and toward the coast of France. Tidal ranges along the coasts of Brittany and Normandy are greater than 4–5 m, whereas along the southwest English coast they are less than 3 m.

11.8.3 Funnel-shaped embayments

The configuration of the coast can also have a pronounced influence on tidal ranges. Rotary tidal waves do not exist in funnel-shaped embayments due to their narrowness. Instead, the tidal wave propagates into and out of funnel-shaped bays. The wave is constricted by the seabed, which shallows in a landward direction, and by the increasingly narrow con-

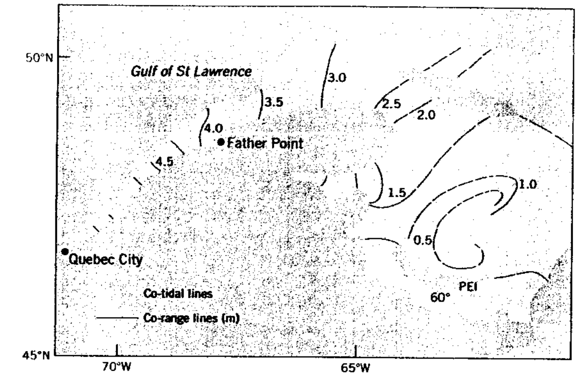


Fig. 11.17 The Gulf of St Lawrence narrows from a width of 150 km at the entrance to the St Lawrence River to less than 15 km wide just downstream of Quebec City. Gradual constriction of the tidal wave in this funnel-shaped embayment increases spring tidal ranges from 1.0 m at the entrance to over 5.0 m at Grosse Isle near Quebec City.

fines of the embayment. Although frictional elements serve to decrease the energy of the propagating wave, the overall steepening of the tidal wave causes an amplification of the tidal range (Fig. 11.17). For example, the 2.0 m tidal range at the entrance to the Saint Lawrence estuary increases to over 5 m during spring tidal conditions at Quebec City, some 600 km upstream. Funnel-shaped embayments are found all over the world, including the Bay of Fundy in Canada (see Box 11.1), the Gironde and Seine estuaries in France, the Wash and the Severn Estuary in the United Kingdom, Cambridge Gulf in Australia, Cook Inlet and Bristol Bay in Alaska, the Gulf of Cambay in India, the head of the Gulf of California, and the Rio de Plata in South America.

11.8.4 Tidal bore

In some estuaries large tidal ranges lead to the formation of tidal bores (Fig. 11.18). A tidal bore is a steep-crested wave or breaking wave that moves upstream with the rising tide. Their occurrence coincides with large funnel-shaped estuaries that have tidal ranges exceeding 5 m and a channel that progressively shallows upstream. The height of most bores is less than 0.4 m but there are some spectacular bores that adventurers surf on as the wave advances upriver. A tidal bore is formed when the propagating tidal wave oversteepens and breaks due to a constriction of the channel and retarding effects of the river's discharge. Tidal bores are best developed during spring tide conditions when tidal ranges are near maximum. Bores are found in the Severn and Trent estuaries in the United Kingdom, the Seine in France, the Truro and Petitcodiac rivers that discharge into the Bay of Fundy, the Ganges in Bangladesh, and several rivers along the coast of China. Some of the largest tidal bores in the world occur in China-tang River in northern China and in the Pororoca River, a branch of the Amazon. Their heights have been reported to approach 5 m and they travel at speeds close to 20 km h^{-1}. Fisherman and shippers will often travel upstream by riding the ensuing strong currents that follow the passage of a tidal bore.

11.8.5 Tidal currents

Tidal currents are most readily observed in coastal regions where the tidal wave becomes constricted. As the tidal wave approaches the entrance to harbors, tidal inlets, and rocky straits, the tide rises at a faster rate in the ocean than it does inside the harbor or bay. This produces a slope of the water surface and, just like a river system, the water flows downhill, producing a tidal current (Fig. 11.19). The water moving through a tidal inlet and flooding a bay is called a **flood-tidal current**. The water emp-

Box 11.1 Bay of Fundy: the largest tides in the world

The Bay of Fundy in eastern Canada is perhaps the most famous funnel-shaped embayment in the world. It has record tides equal to the height of a five-story building. The bay connects to the northern end of the Gulf of Maine and separates the provinces of New Brunswick and Nova Scotia (Fig. B11.1). The formation of the bay is related to the opening of the Atlantic Ocean, which occurred about 180 million years ago when North America began separating from Europe and northern Africa. The bay is part of a rift valley that developed within a broad sandy arid plain. Remnants of basaltic eruptions associated with early rifting can still be found at several locations along the bay's margin. During repeated episodes of Pleistocene glaciation, ice sheets scoured and deepened the basin and then deposited a thick carpet of glacial sediment. Following deglaciation, isostatic rebound (see Chapter 17) caused the sea to retreat from the Bay of Fundy, exposing the basin to riverine reworking. Approximately 6000 years ago, rising eustatic sea level inundated the bay and allowed waves to erode the soft sedimentary rocks that surround most of the Bay of Fundy shoreline. Sandstone cliffs, intertidal marine platforms, and vast sand shoals are a product of this erosion.

The Bay of Fundy is 260 km long and 50 km wide at its opening, gradually narrowing into two separate bays: Chignecto Bay to the northeast and the Minas Basin to the east. It is deepest at its mouth and progressively shoals toward its eastern end, with an average depth of about 32 m along its length. The immense tidal range in the Minas Basin (Fig. B11.2) leads to more than 14 km^3 of water flushing the bay twice daily (actually every 12 hours and 25 minutes). Tidal currents at the entrance to the Minas Basin exceed 4 m s^{-1}. These strong currents mold the sandy bottom into giant sand ripples called sandwaves, which have heights of more than 10 m. Flow in the 5 km wide tidal channel leading into the Minas Basin is equal to the combined discharge of all the streams and rivers on Earth. The weight of the huge volume of water entering the Minas Basin actually causes a slight tilting of western Nova Scotia.

Although the funnel shape of this coast contributes to very large tides, it is **tidal resonance** that generates the world's largest tidal ranges. The length and depth of the Bay of Fundy promote the development of a standing wave (similar to the sloshing back and forth of water in a bathtub or a coffee cup) that is

(a)

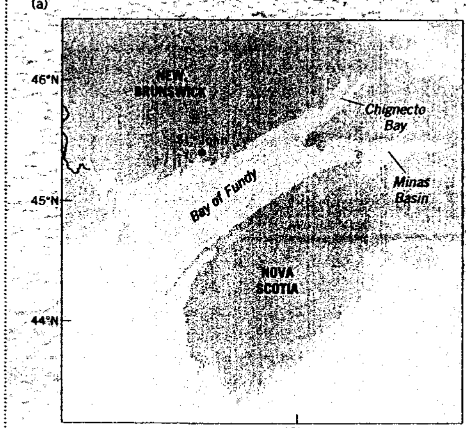


Fig. B11.1 Location map of the Bay of Fundy.

Box 11.1 (*cont'd*)

constructively perturbed by the tide-generating forces in the Atlantic Ocean. Resonance occurs in elongated embayments when the advancing tidal wave reflects off the head of the bay back toward the bay's entrance. A standing wave is produced when the geometry of the bay is of the correct dimensions, such that the reflected wave arrives at the bay entrance at the same time as the next incoming tidal wave. Each incoming wave amplifies the standing wave until the energy that is added balances the energy lost due to friction. Tidal ranges at the mouth to the Bay of Fundy are a modest 3 m but resonance and funneling effects gradually increase the range to an amazing 16 m near Wolfville at the eastern end of the Minas Basin (Fig. B11.3).

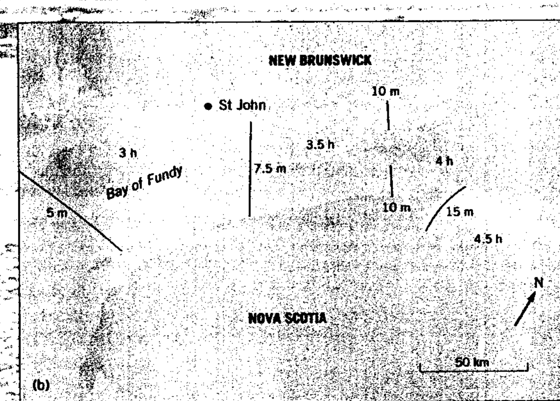


Fig. B11.2 Co-range and co-tidal lines for the Bay of Fundy.

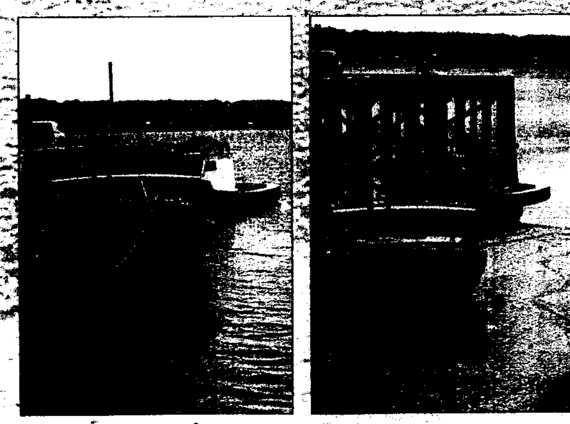


Fig. B11.3 Pictures illustrating large tidal ranges, showing high and low tides.

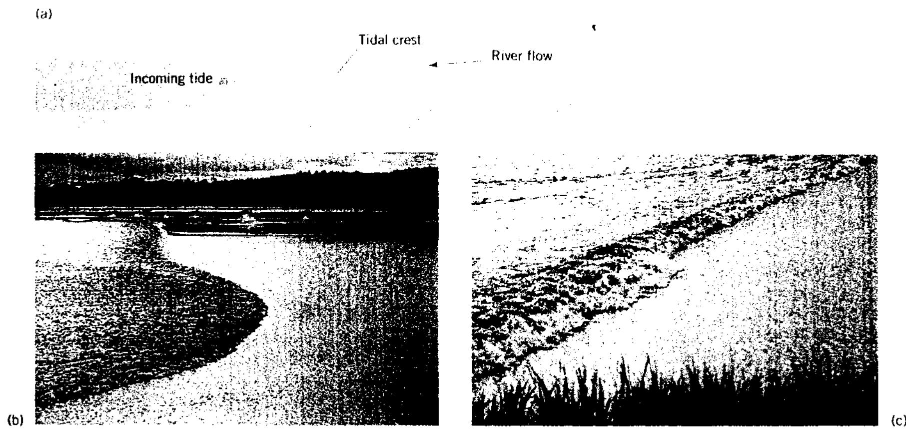


Fig. 11.18 Tidal bores occur in funnel-shaped estuaries with tidal ranges greater than 5 m. (a) They are produced when shoaling and constriction of the landward moving tidal wave oversteepens and may begin to break. (b) View of tidal bore in the Salmon River in the Minas Basin along the Bay of Fundy, Nova Scotia. (c) Close-up view of tidal bore, which is approximately 30 cm in height.

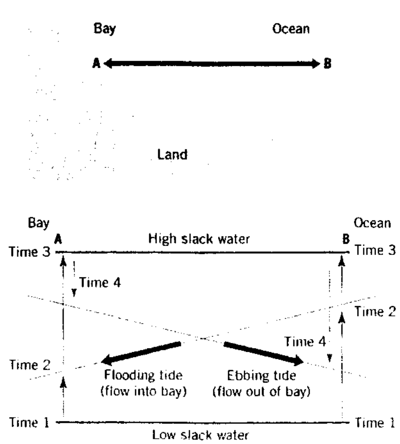


Fig. 11.19 Tidal currents occur at the entrance to bays, harbors, and tidal inlets and are due to a constriction of the tidal wave.

tying out of a bay and moving seaward is referred to as an **ebb-tidal current**. In a slight oversimplification, when the tidal waters in the ocean and bay are at the same elevation, there is **slack water** at the tidal inlet. This condition usually occurs at high tide and low tide. Likewise, the strongest current velocities are produced when the water surface through the inlet achieves the steepest slope, which commonly is near midtide but may also occur closer to high or low tide. During spring tide conditions when the maximum volume of water is exchanged between the ocean and bay, tidal currents can reach velocities of 3 m s^{-1}.

Along non-sandy shorelines, tidal currents can achieve strong current velocities, particularly in regions with large tidal ranges, large bay areas, and narrow constrictions. One such location is along the Norwegian coast north of Bodø where Vestfjord connects to the Norwegian Sea. The fierce tidal currents that flow through the straits reach speeds greater than 4.0 m s^{-1}. This creates strong whirlpools that make travel through the strait extremely dangerous during peak current flow. The Norwegians call these whirlpools the **maelstrom** and fishermen time their passage to avoid these perilous eddies.

The strong tidal currents that are generated in funnel-shaped estuaries and elsewhere along the world's coastlines can be harnessed to provide a source of energy. For example, in the Gulf of Saint Malo along the Brittany coast of France the tidal range in the Rance Estuary can exceed 12 m. This exceptional large tidal fluctuation produces very strong tidal currents. A 750 m wide barricade has been constructed across the river and houses 24 hydroelectric power stations. The reversing tidal currents of the Rance have been providing electricity since 1966.

11.9 Summary

The Moon's and the Sun's force of attraction exerted on the Earth's hydrosphere causes ocean tides. The Moon's tide-generating force is about twice that of the Sun because it is much closer to the Earth. The Moon and Earth revolve around a common center of mass inside the Earth, which produces a centrifugal force that balances the forces of attraction. In the equilibrium tide model, two tidal bulges are developed because masses on the Earth's surface are acted on unequally by gravitational and centrifugal forces. One bulge faces the Moon and the other is directed away from the Moon. The tidal period is 12 hours and 25 minutes rather than 12 hours (half of the Earth's rotation) because it takes the Earth an additional 50 minutes each day to catch up with the Moon in its orbit. As the Moon revolves around its common center of mass with the Earth its orbit makes excursions north and south of the equator. When the Moon is over the tropics, the Earth passes through unequal successive tidal bulges, producing different elevations in successive high and low tides and unequal tidal ranges. This tidal condition is called a semi-diurnal inequality.

The effects of the Sun can enhance or retard the Moon's tide-generating force. When the Moon, Earth, and Sun are aligned (a position called syzygy), the Sun's effects are additive and we experience spring tides and large tidal ranges. When the Moon, Earth, and Sun are at right angles (quadratic position), the Sun's effects diminish the Moon's tide-generating forces and we have neap tides and relatively small tidal ranges. Mean tides and average tidal ranges occur between syzygy and quadratic positions. Due to the elliptical orbits of the Moon and Earth, the height and range of the tides increases when the Moon is proximate to the Earth (perigean tides) and the Earth is close to the Sun (perihelion tides).

The continents and island archipelagos partition the Earth's hydrosphere into several interconnected large and small ocean basins. Based on their dimensions, Coriolis and tide-generating forces cause the tidal wave to rotate around one or more amphidromic points within these basins, counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. Tidal range increases with distance from the amphidromic point but ranges in the open ocean are generally quite low (<0.6 m). When the tidal wave propagates across the continental margin the wave slows down and the crest steepens, resulting in an increase in the tidal range (1.0–2.0 m at the coast). The tidal signature along the coast reflects the geometry of the basin and shoaling behavior of the tidal wave. Most open ocean coasts experience semi-diurnal tides (two tides daily) or mixed tides, which is a tidal signature that exhibits periods of semi-diurnal tides, and distinctly diurnal (one tide daily) tides during other portions of the lunar month. Diurnal tides are most common in restricted basins where the tidal wave resonates with a period close to 24 hours and 50 minutes.

The tidal wave can undergo dramatic distortions as it moves into restricted ocean basins and through straits due to Coriolis effects and shoaling effects. Deformation of the tidal wave can result in dramatic differences in tidal range over distances less than 50 km. This is particularly apparent in funnel-shaped embayments, where steepening of the advancing tidal wave can increase the tidal range by 2–4 m at the head of the bay. Even greater tidal ranges can result if a standing wave is produced in the bay that is constructively interfered by the incoming tidal wave. This phenomenon is best developed in the Bay of Fundy, where tidal ranges (up to 16 m in the

Minas Basin) are the largest in the world. In some estuaries with very large tidal ranges, the advancing tidal wave steepens, forming a steep-crested wave or breaking wave called a tidal bore, which moves upstream with the rising tide. Tidal currents are produced in coastal settings when the tidal wave becomes constricted, such as at the entrance to a bay or tidal inlet.

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12 Tidal inlets