Introduction to Ocean Sciences

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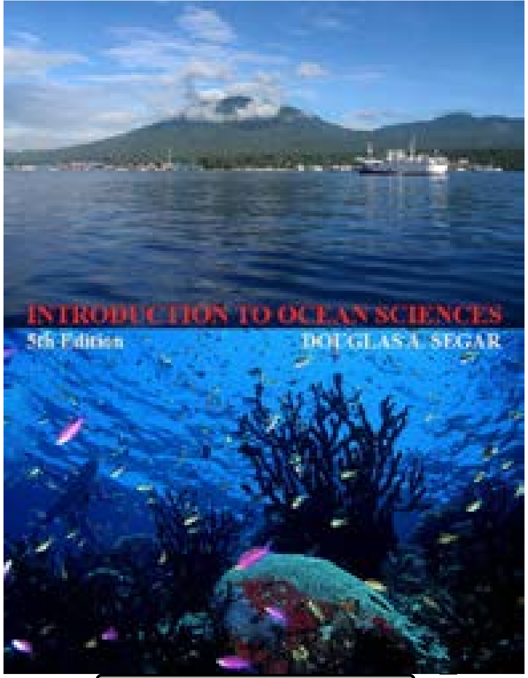

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CHAPTER 10

Tides

CRITICAL CONCEPTS USED IN THIS CHAPTER

CC12 The Coriolis Effect

These two sets of photographs were taken from the same location 6 h apart at the port of Anchorage, Alaska, at approximately high tide and low tide. The tidal range this day was almost 11 m. For scale, note the cargo containers on the stern of the ship. They are the type hauled on 18-wheel trucks or flatbed railcars.

Most of us are familiar with the water movements that slowly expose and then cover the seaward part of the **shore** during a day. This rise and fall of sea level is called the **tide**. If we observe tidal motions long enough at one location, we will see that they are periodic. At some locations, the tide rises and falls twice during a day; at others, it rises and falls only once. The times of high and low tide vary predictably, and the height of the tide also changes somewhat from day to day. Indeed, the **tidal range** is often very different for the two tides on a single day. In addition, we may observe that the sea-level change between high and low tide is large in some places, while in other places there appears to be no tide at all.

Tides are important to mariners because many harbors and channels are not deep enough for vessels to navigate at low tide. Tides are an energy source that has been harnessed for electricity generation in some parts of the world. They are also important to many marine creatures, especially **species** that live in the **intertidal zone** between the **high-tide line** and **low-tide line** and must cope with alternate periods of immersion in water and exposure to air.

Tides cause tidal **currents** that can be very swift in coastal waters and within harbors and **estuaries**. In estuaries, tidal currents reverse direction as the tide rises and falls. When the current flows in from the sea, it is a **flood** current. When it flows out, it is an **ebb** current. The reversals between flood and ebb currents do not necessarily occur at high or low tide. However, where only one tide occurs each day, there is one flood and one ebb; and where two tides occur each day, there are two floods and two ebbs.

In the deep ocean tides produce generally weaker currents than in coastal waters. However, throughout the oceans depths tidal motions are responsible for generating currents that interact with density differences between water layers and with seafloor topography to cause internal waves, eddies, and turbulence that is a major contributor to the vertical mixing of deep layer water upwards as part of the MOC discussed in **Chapter 8**.

It has been known for more than 2000 years that tides are related to the movements of the sun and moon. However, the relationship was not fully explained until 1686, when Sir Isaac Newton published his theory of **gravity**. Tides are a phenomenon that are controlled entirely by a few simply physical principles, yet they can be extraordinarily complex.

TIDE-GENERATING FORCES

Tides continuously raise and lower the sea surface. The vertical movement of the water surface is as much as several meters, twice a day in some areas. Clearly large amounts of energy are necessary to move the water involved in this process. The energy is supplied by the gravitational attraction between the water and the Earth, moon, and sun—but how? Tides are cyclical, but they do not come and go at the same times each day, and the height to which the water rises or recedes varies from day to day. Why does this happen? To answer these questions, we must first learn some basic information about gravity and the motions of the moon around the Earth and the Earth around the sun.

Gravity

Newton's law of gravitation states that every particle of mass in the universe attracts every other particle of mass with a force that is proportional to the product of the two masses and inversely proportional to the square of the distance between the two masses. The gravitation force (F) between two masses can be expressed as

$$F = G \times \frac{M_1 \times M_2}{D^2}$$

where G is the gravitational constant (a constant defined by Newton's law and equal to $6.673 \times 10^{-11} \mathrm{m \cdot kg^{-1} \cdot s}$), M_1 and M_2 are the two masses, and D is the distance between them.

For approximately spherical objects, such as planets, the entire mass can be considered to be at the object's center of gravity, and the distance D is measured between the centers of the two masses. The gravitational force increases as either mass increases or the distance between the two objects decreases.

We are familiar with gravity because it is the force that attracts all objects on the Earth's surface, including ourselves, to the much greater mass of the Earth itself. In addition, the Earth and every object on it are subject to gravitational attractions toward the sun, the moon, other planets, and every other celestial body. In the following discussion in this chapter we refer to Earth's gravitational force that we experience on its surface as gravity while we refer to the gravitational force between celestial objects such as the Earth and moon as gravitational attraction but this is simply to minimize possible confusion as the phenomena are the same and the laws of gravity apply to both.

Gravitational forces are extremely small in relation to the gravity we experience on Earth's surface. Although the sun, stars, and some planets each have a mass much greater than the Earth's mass, they are much farther away from us than we are from the Earth's center. For example, gravitational attractions that the sun and moon exert on any object at the Earth's surface are approximately 0.06% and 0.0003% of the Earth's gravity, respectively. Gravitational attractions of other celestial bodies are much smaller.

Although they are almost negligible in comparison with the Earth's gravity, gravitational forces exerted by the moon and sun on the Earth are the cause of the tides. To understand how these forces cause the tides, we must first consider the characteristics of orbits in which celestial bodies move.

Orbital Motions and Centripetal Force

Any two bodies that orbit together in space, orbit around their common center of mass. This works like a seesaw. If the two riders are of equal weight, the seesaw balances when the riders are equal distances from the center. Similarly, two planetary bodies of equal mass would orbit around a point exactly midway between them. However, if one rider is heavier than the other, the heavier rider must sit closer to the center of the seesaw to make it balance. Similarly, two planetary bodies of unequal masses orbit around a point that is closer to the more massive of the two bodies. The Earth's mass is 81 times that of the moon. Therefore, the common point of rotation is about 4680 km from the Earth's center, or approximately 1700 km below the Earth's surface (**Fig. 10-1**). Similarly, because the sun has far greater mass than the Earth, the common point of rotation of the Earth and the sun is deep within the sun.

As two planetary bodies orbit each other, they must be constrained in their orbit by a **centripetal force** that prevents each from flying off in a straight line (**CC12**). The centripetal force is supplied by the gravitational attraction between them. The centripetal force required is the same for all parts of each of the two bodies. Because centripetal force varies with distance from the center of rotation (**CC12**), this may be difficult to

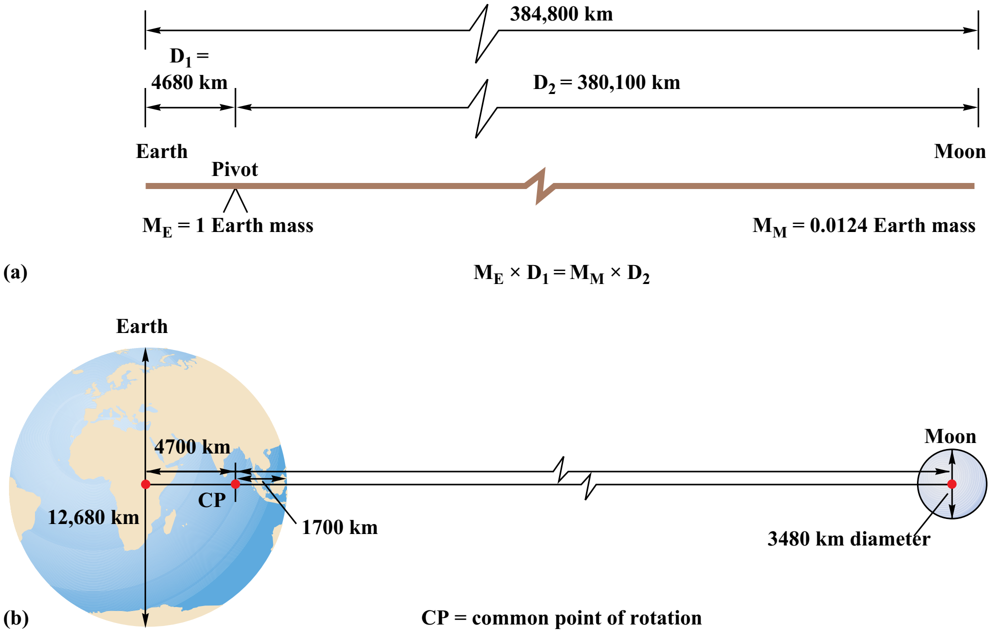


FIGURE 10-1 Any two bodies in space orbit around a common point of rotation. Just as, on a seesaw, the heavier person must sit nearer the pivot point to provide balance, the common point of rotation for two bodies orbiting in space must be closer to the more massive body. (a) Thus, the Earth's center must be much closer to the common center of rotation than the moon's center is. (b) Because the Earth is much more massive than the moon, their common point of rotation is approximately 1700 km below the Earth's surface.

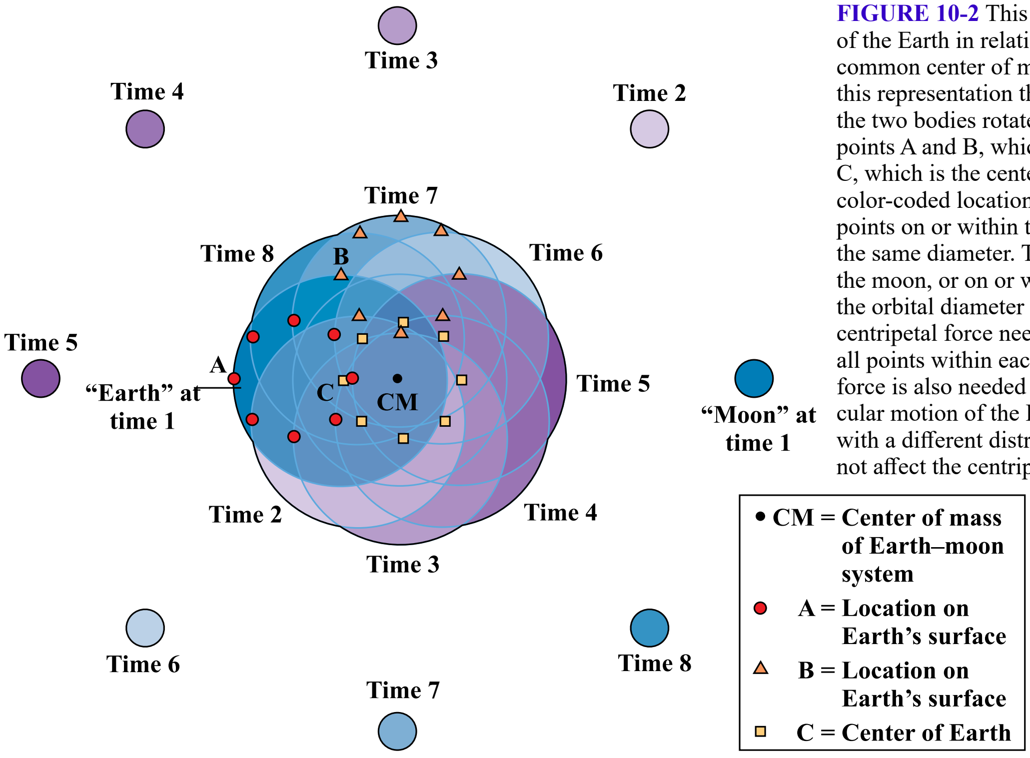


FIGURE 10-2 This figure is a representation of the location of the Earth in relation to the moon as they orbit around their common center of mass (CM), which is inside the Earth. In this representation the Earth is assumed to be nonrotating. As the two bodies rotate around their common center of rotation, points A and B, which are at the Earth's surface, and point C, which is the center of the Earth, would move through the color-coded locations shown in the figure. Notice that all points on or within the Earth move in circular paths that have the same diameter. This is also true for all points on or within the moon, or on or within any other orbiting bodies. Because the orbital diameter and rotation rate are always the same, the centripetal force needed to keep each body in orbit is equal at all points within each of the two bodies. Note that a centripetal force is also needed to maintain parts of the Earth in the circular motion of the Earth's spin, but this is a separate motion with a different distribution of its centripetal force and does not affect the centripetal force between the Earth and moon.

understand. However, within either of the orbiting bodies, all particles of mass move at the same speed in circular paths of the same diameter. We can understand this motion if we examine the motions of the two objects as they orbit each other without considering other motions, such as the Earth's spin on its axis or orbits that involve a third body.

Figure 10-2 shows a non-spinning planet (a hypothetical "Earth") orbiting with another planetary object (a hypothetical "moon"). In this diagram, the common center of rotation, which is also the center of mass of the two bodies, is located beneath the surface of the larger planetary body (the hypothetical Earth). Careful examination of **Figure 10-2** reveals that, as the two bodies rotate around each other, each particle of mass on the planet moves in a circular orbit, and all of the orbits have the same diameter. However, as **Figure 10-2** shows, the centers of the circular orbits are all displaced from the common center of rotation, except the orbit of the planet's center of mass. Because the particles of mass in the planet move in circles of the same diameter and complete the circles in the same amount of time, all particles require the same centripetal force to maintain their orbits. This is true no matter where the common center of rotation is. It is true for the Earth–moon system, where the center of rotation is inside the Earth, and for the Earth–sun system, where the center of rotation is inside the sun.

The Balance between Centripetal Force and Gravitational Force

The total gravitational force between the moon and the Earth (or the sun and the Earth) must be equal to the total centripetal force needed to maintain these bodies in their orbits, or else the orbits would change. Although all particles of mass within the Earth are subject to the same centripetal force, the gravitational

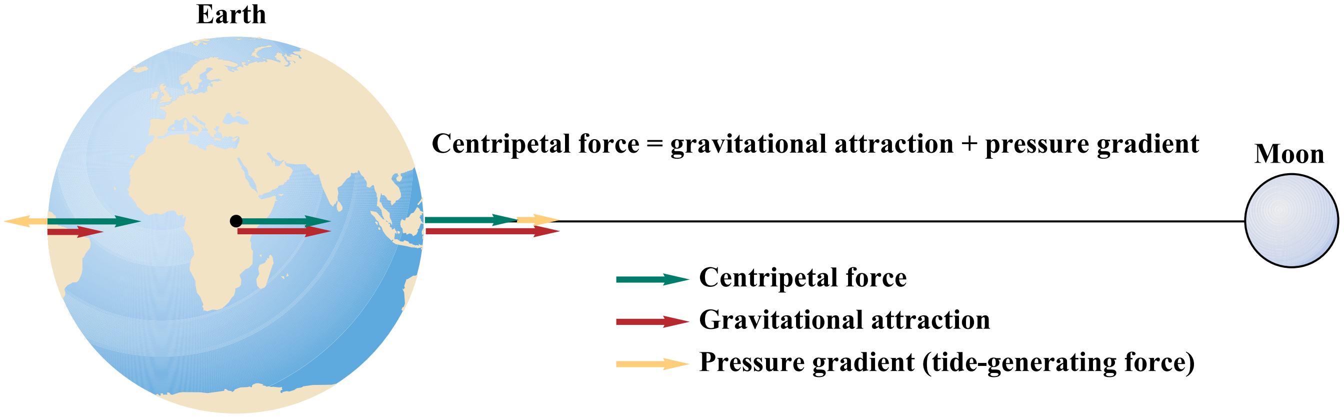


FIGURE 10-3 The total gravitational force between the Earth and moon (or sun) must equal the total centripetal force needed to maintain the two bodies in their common orbit. However, because the gravitational force varies slightly at different points on the Earth, whereas the centripetal force is the same at all points, there is a slight imbalance between them everywhere except at the exact center of mass of the Earth. On the side of the Earth nearest the moon, the gravitational force due to the moon is slightly higher than it is at the Earth's center. The slight excess of gravitational force over centripetal force at this point is easily compensated by the pressure gradient. Similarly, there is a slight excess of centripetal force over gravitational force on the Earth at the point directly away from the moon. Thus, objects at points directly under the moon or directly opposite the moon weigh very slightly less than they do at other points on the Earth.

force on each particle of mass within the Earth varies with its distance from the moon or sun. For example, the distance from the moon's center to the Earth's center is approximately 384,800 km, and the Earth's diameter is approximately 12,680 km. Therefore, a point on the Earth's surface nearest to the moon is only 378,460 km from the moon's center, and a point farthest from the moon is 391,140 km from the moon's center. Because the gravitational force is inversely proportional to the square of the distance, the change in the moon's gravitational force between the point on the Earth nearest to the moon and the Earth's center is 378,4602 divided by 384,8002, or about 1 to 1.034. Hence, the moon's gravitational attraction is about 3% greater at the Earth's surface nearest the moon than it is at the Earth's center (the average gravitational attraction between moon and Earth). Similarly, the moon's gravitational attraction at the Earth's surface farthest from the moon is about 3% less than the average gravitational attraction.

The average centripetal force for each orbiting body must equal the average gravitational force between the two if the orbit is to remain stable. Because the centripetal force is the same at all points on the Earth and gravitational force is not, there is a net excess gravitational force on the side of the Earth nearest the moon, and a net deficit of gravitational force on the side farthest from the moon (Fig. 10-3). These imbalances, are tiny in relation to the Earth's gravity and are easily compensated in the solid Earth by small changes in **pressure gradient** (the gradient of pressure within the atmosphere, ocean, or solid Earth that increases toward the Earth's center). Pressure within the Earth (and other objects) represents the force needed to resist the gravity tending to pull all material toward the Earth's center). For people, the compensation in the pressure gradient causes a change in weight. Each of us weighs about 0.000,000,1 kg (0.1 mg) less when the moon is over the opposite side of the Earth and when it is directly overhead than when the moon is just below the horizon—much too small a difference to notice.

Unlike solid objects, ocean water can flow in response to the imbalances between gravitational force and centripetal force. These flows are the tides. For convenience, we refer to the net excess of gravitational force over centripetal force as the "tidal pull" or "tide-generating force".

Distribution of Tide-Generating Forces

At the point on the Earth's surface nearest the moon, there is a slight tidal pull. Water is pulled upward toward the moon at this point. However, the Earth's gravity, which is comparatively very strong, acts directly opposite the tidal pull at this location. Therefore, the tidal force at this point (and at the opposite side of the Earth, which is farthest from the moon) has little effect, just as the tidal force has only an extremely small effect on our weight.

At other points on the Earth's surface, the tidal pull is exerted in a direction different from that of the Earth's gravity because the direction between that point on the Earth's surface and the moon, and the direction between that point and the Earth's center of mass, are aligned at an angle. Thus, at every point except directly under the moon and exactly on the other side of the Earth, the tidal pull has a component that acts parallel to the Earth's surface (Fig. 10-4). This component of tidal pull, which is refered to as the "tidal force" cannot be compensated by the Earth's gravity and therefore causes water to flow in the direction of the force.

The net result of the tidal forces acting on the Earth's oceans is to move water toward the points nearest to the moon and farthest from the moon (Fig. 10-4b). This movement creates bulges of elevated water surface at these points, and a depression of the water surface in a ring around the Earth halfway between these points. The diagrams in this book necessarily greatly exaggerate the bulges. Even on an Earth totally covered by oceans, the bulges would be less than a meter high.

The tide bulges are oriented directly toward and away from the moon. Because the Earth is spinning, the point on the Earth facing the moon is continuously changing. Therefore, as the Earth spins on its axis the bulge remains aligned with the moon, but the locations on the Earth that are under the tide bulge change.

Relative Magnitude of the Lunar and Solar Tide-Generating Forces

Although all planets and stars exert tidal forces on the Earth, only tidal forces of the moon and the sun are significant. Tidal forces are caused by the small difference in gravitational force

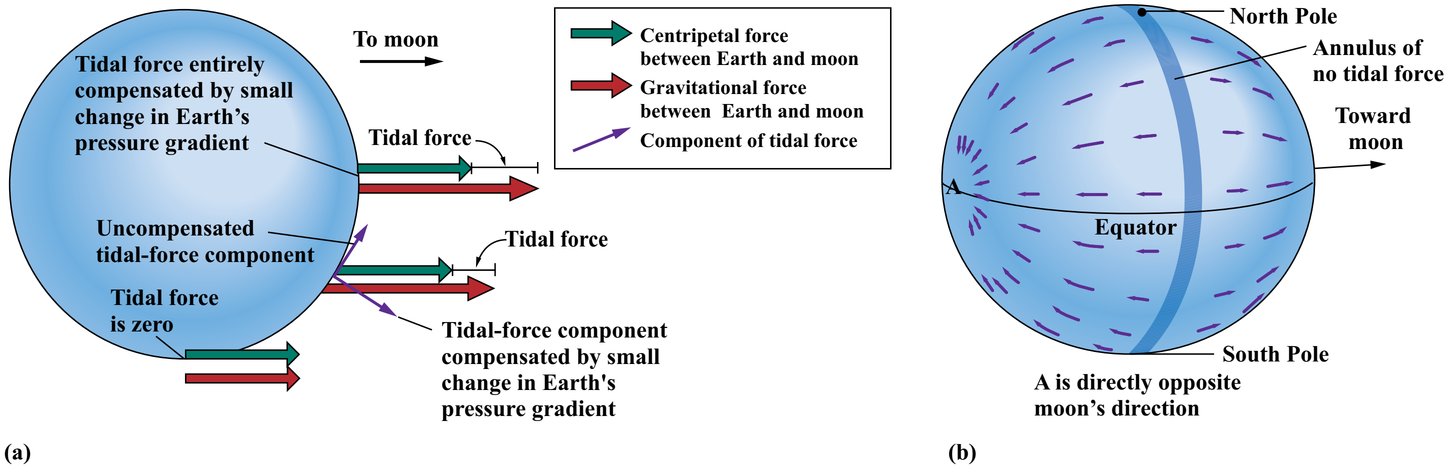


FIGURE 10-4 Horizontal tidal forces. (a) Components of gravitational attraction, centripetal force, and the Earth's pressure gradient. The vertical component of the tidal force is easily compensated by a minute change in the pressure gradient. Magnitudes of the tidal force and tidal force components are highly exaggerated in the figure. (b) The horizontal tidal force is zero at a point directly under the moon (or sun) and a point located exactly on the opposite side of the moon. It is also zero in a ring (annulus) around the Earth that is equidistant from these two points. The horizontal tidal force increases to a maximum and then decreases between the point directly under the moon and the annulus where the force is zero. The same is true between the point directly away from the moon and the annulus, but the tidal force is in the opposite direction.

from one side of the Earth to the other. This difference depends on the distance between the Earth's center and the other body's center, and on the other body's mass. Although we need not perform the calculation here, we can show mathematically that the magnitude of the tidal force is proportional to the mass of the attracting body (sun or moon) and inversely proportional to the cube of the distance between the centers of the two bodies (r^3). This means that the tidal force is much more dependent on the distance between bodies than it is on mass.

For the Earth–moon system, the tide-generating force (F_M) is given by

$$F_M = K \times \frac{\text{(Mass of Moon)}}{\text{(Earth-to-moon distance)}^3}$$

and for the Earth–sun system, the tide-generating force (F_S) is given by

$$F_S = K \times \frac{\text{(Mass of Sun)}}{\text{(Earth-to-sun distance)}^3}$$

where K is a constant that is always the same for tidal forces between the Earth and any other planetary body.

The sun's mass is about 27 million times greater than the moon's. However, the sun is about 390 times farther from the Earth. The ratio of solar to lunar tidal force can be calculated with the following equations:

$$\frac{F_\text{S}}{F_\text{M}} = \frac{\text{(Mass of Sun)}}{\text{(Mass of Moon)}} \times \frac{\text{(Earth-to-moon distance)}^3}{\text{(Earth-to-Sun distance)}^3}$$

$$= \frac{27{,}000{,}000}{1} \times \frac{(1 \times 1 \times 1)}{(390 \times 390 \times 390)}$$

$$= 0.46$$

Despite the sun's much greater mass, its tide-generating force is only about 46% of the moon's tide-generating force because the sun is much farther away from the Earth.

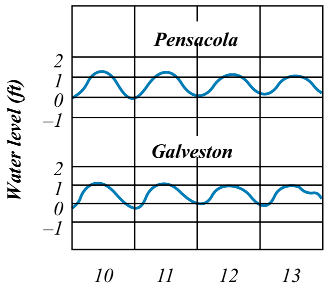
CHARACTERISTICS OF THE TIDES

Tides are measured by a variety of gauges that continuously monitor the sea surface height. The tide is described by a plot of the water surface height as a function of time, called a "tidal curve" (Fig. 10-5). The tidal curves in Figure 10-5 show that tidal motions are similar to the **progressive waves** described in Chapter 9. In some locations, the tidal curve resembles a simple progressive wave. In other locations, it resembles the complex waveforms produced when waves of different **wave periods** and **wave heights** interfere. Tidal curves are, in fact, the net result of several tide waves of different periods, as explained in the next section.

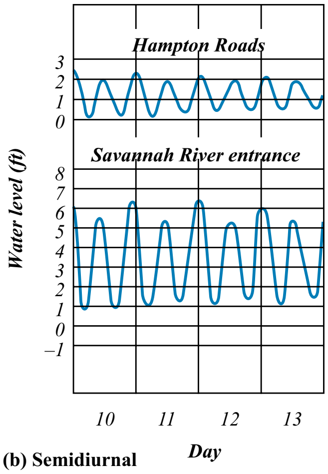
The most important characteristics of a tidal curve are the times and relative elevations of high tide and low tide, and the tidal range, which is the difference between the height of the high tide and that of the low tide (Fig. 10-5). Because the tide is a wave, the tidal range is an expression of the tide wave height.

Diurnal, Semidiurnal, and Mixed Tides

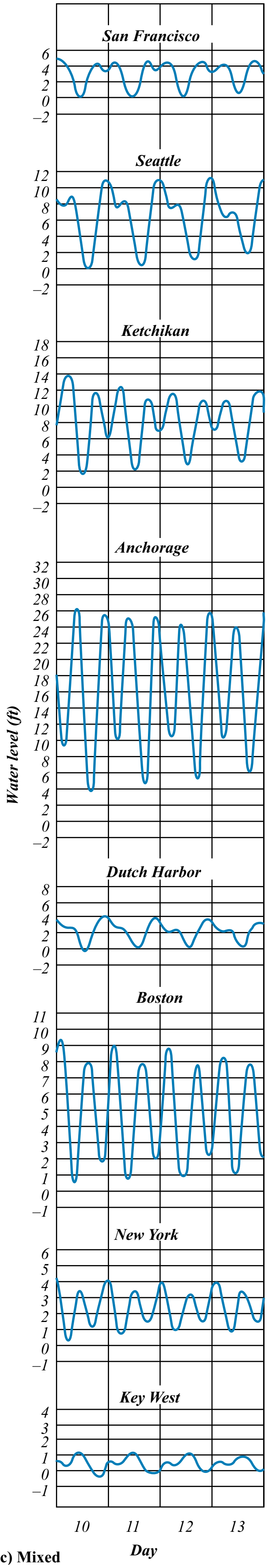
Tides are classified into three general types based on the number and relative heights of the tides each day at a given location. **Diurnal tides** (or daily tides) have one high tide and one low tide in each tidal day, which equals approximately 24 h 49 min (Fig. 10-5a). The next section explains why the tidal day is 49 min



(a) Diurnal



(b) Semidiurnal



(c) Mixed

FIGURE 10-5 Selected tide records. (a) Diurnal tides occur at Pensacola, Florida, and Galveston, Texas. (b) Semidiurnal tides occur at Hampton Roads, Virginia, and the Savannah River entrance, Georgia. (c) Mixed tides occur at most locations, including San Francisco, California; Seattle, Washington; Ketchikan, Anchorage, and Dutch Harbor, Alaska; Boston, Massachusetts; New York, New York; and Key West, Florida. Note that even the Hampton Roads and Savannah River tides are not pure semidiurnal tides, but they are nearly so. Tidal heights are in feet because tide tables issued by the U.S. government still use these units.

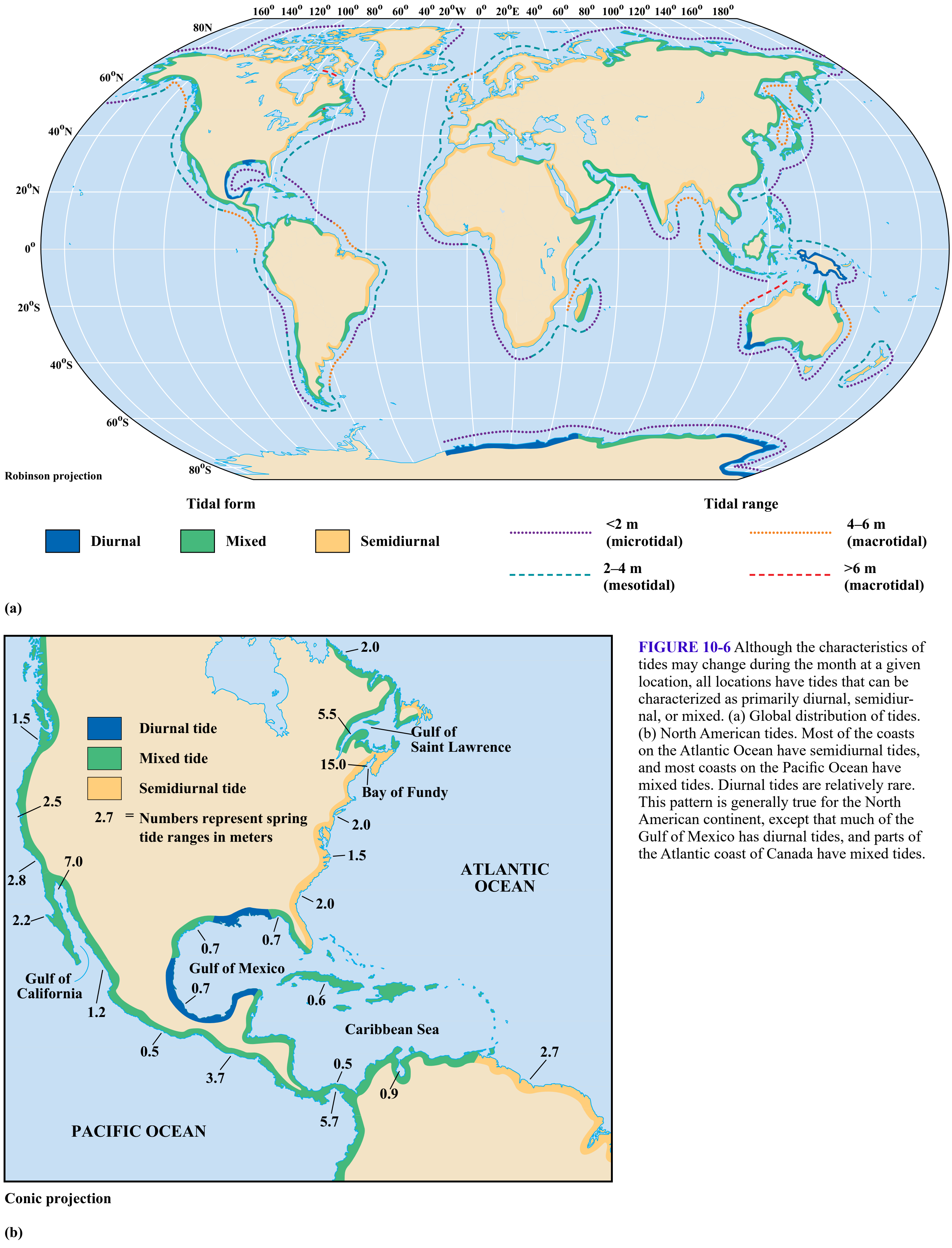


FIGURE 10-6 Although the characteristics of tides may change during the month at a given location, all locations have tides that can be characterized as primarily diurnal, semidiurnal, or mixed. (a) Global distribution of tides. (b) North American tides. Most of the coasts on the Atlantic Ocean have semidiurnal tides, and most coasts on the Pacific Ocean have mixed tides. Diurnal tides are relatively rare. This pattern is generally true for the North American continent, except that much of the Gulf of Mexico has diurnal tides, and parts of the Atlantic coast of Canada have mixed tides.

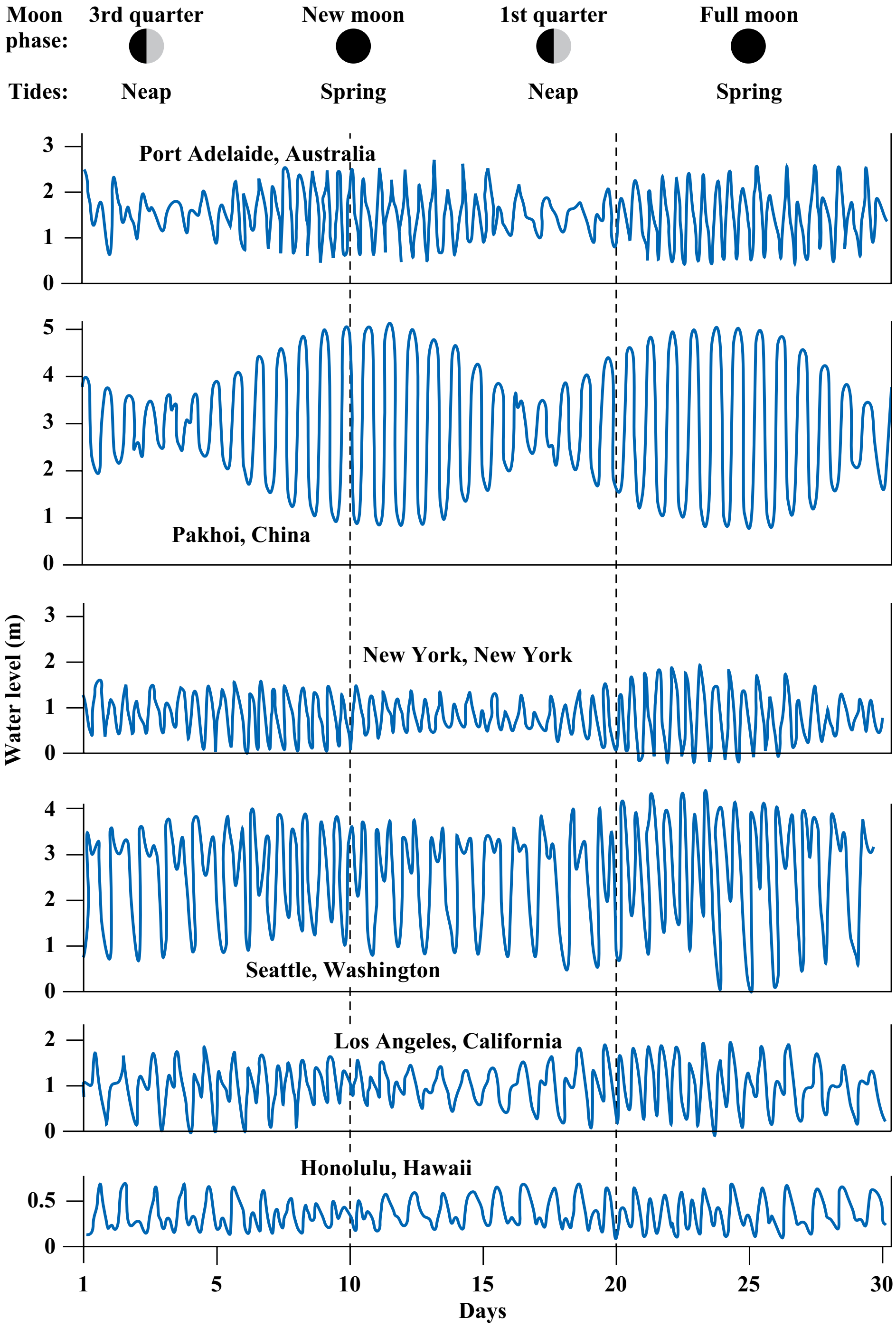


FIGURE 10-7 Monthly tide records show the twice-monthly occurrence of spring tides associated with new moon and full moon, and the twice-monthly occurrence of neap tides associated with the quarter moons. This pattern occurs at all of the locations shown, but it is more pronounced in some areas, such as Port Adelaide, Beihai, and New York.

longer than the solar day. **Semidiurnal tides** (or semidaily tides) have two high and two low tides each tidal day, and thus a period of 12 h 24½ min. For pure semidiurnal tides, the two high tides (and the two low tides) each day are equal in height (**Fig. 10-5b**).

Mixed tides also have two high tides and two low tides each tidal day, but the heights of the two high tides (and/or of the two low tides) in each tidal day are different (**Fig. 10-5c**). Mixed tides have a higher high water (HHW) and a lower high water (LHW), as well as a higher low water (HLW) and a lower low water (LLW), each day. **Figure 10-5c** shows that the relationship of these four daily extreme levels varies greatly among different locations.

Mixed tides are the most common. On the North American continent, tides are mixed along the entire Pacific **coast**, on the Atlantic coast of Canada north of Nova Scotia, in the Caribbean Sea, and in parts of the Gulf of Mexico (**Fig. 10-6**). Tides are semidiurnal along the Atlantic coast of the United States and southern Canada, and are **diurnal** only in certain parts of the Gulf of Mexico (**Fig. 10-6**). However, pure semidiurnal and diurnal tides are rare. All tides have some mixed character, but the classifications are useful to mariners and to illustrate the complex tidal motions. In some locations, tides may change in character during the tidal month. For example, they may be semidiurnal for one part of the month and mixed for another part.

Spring and Neap Tides

If we look at tide records for various locations over a period of a month, we see that the daily tidal range varies during the month (**Fig. 10-7**). This variation occurs at all locations, regardless of whether tides are diurnal, semidiurnal, or mixed. Although the variations are often complex, the daily tidal range generally reaches a maximum twice during each lunar month (29½ days). The tidal range thus oscillates back and forth twice each lunar month. Tides with the largest tidal range during the month are spring tides. Tides with the smallest tidal range are neap tides. Two sets of spring tides and two sets of neap tides occur each lunar month.

If we look at tide records for an entire year or for several years, we find that the tidal range varies during the year and between years. However, these variations are much less than the variation between spring and neap tidal ranges during the lunar month.

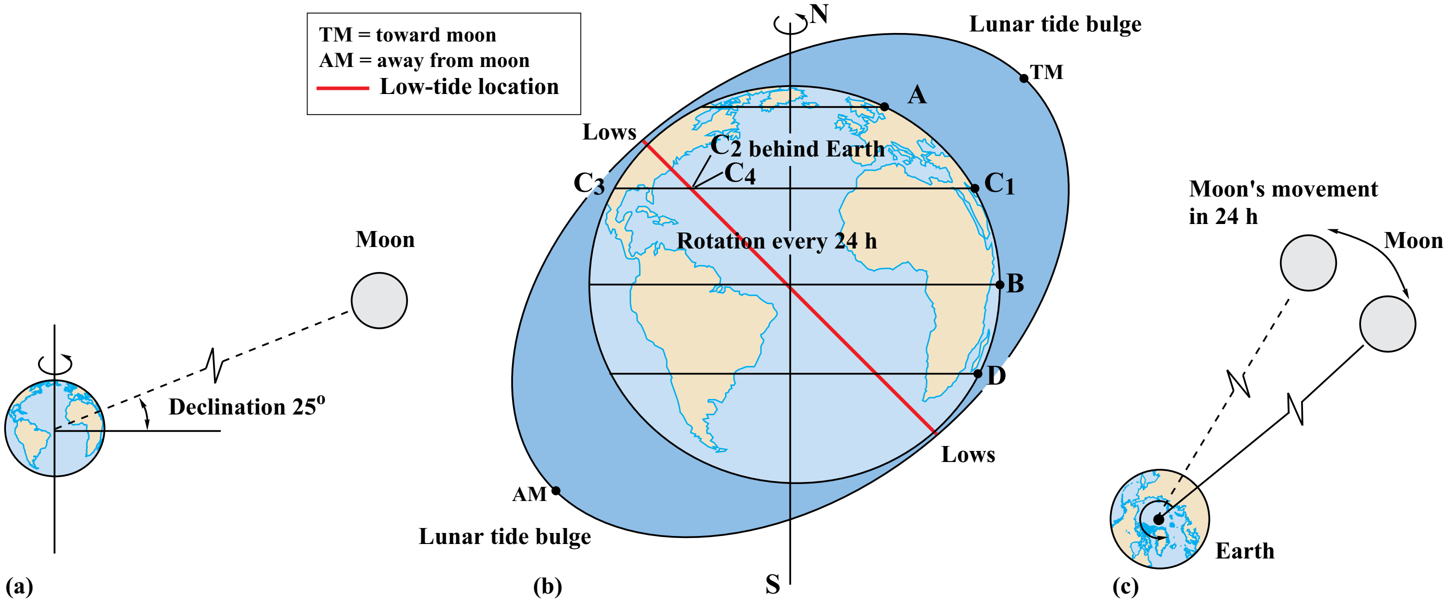
TIDES ON AN OCEAN COVERED EARTH

We can understand many features of tides and their variability by examining the theoretical effect of the sun and moon on a hypothetical planet Earth that is entirely covered by deep oceans and has no **friction** between water and the seafloor. This approach is the basis of equilibrium tide theory.

The Fundamental Equilibrium Tides

Earth spins on its axis once every 24 h. At the same time, the moon orbits the Earth in the same direction as the Earth's spin, but much more slowly (**Fig. 10-8**). By the time the Earth has made one complete rotation (24 h), the moon has moved forward a little in its orbit. The Earth must turn for an additional 49 min before it "catches up" with the moon. Hence, 24 h and 49 min elapse between successive times at which the moon is directly overhead at a specific location on the Earth's surface. This is why the moon rises and sets almost an hour later each night.

On a hypothetical planet covered by oceans and without friction, we can consider what would be the effect of the moon alone during a solar day (**Fig. 10-8**). The moon would create upward bulges on the oceans at points aligned directly toward and directly away from the moon. As the Earth spun, the tidal forces would continue to pull water toward these points. The tide bulges would remain aligned with the moon as the Earth rotated, so the bulges would appear to migrate around the Earth each day. However, the moon does not always orbit directly over the equator. Instead, the angle between the moon's orbital plane and the equator, called the **declination**, varies with time during the lunar month and on longer timescales (**Fig. 10-8a**). For now, we need only consider



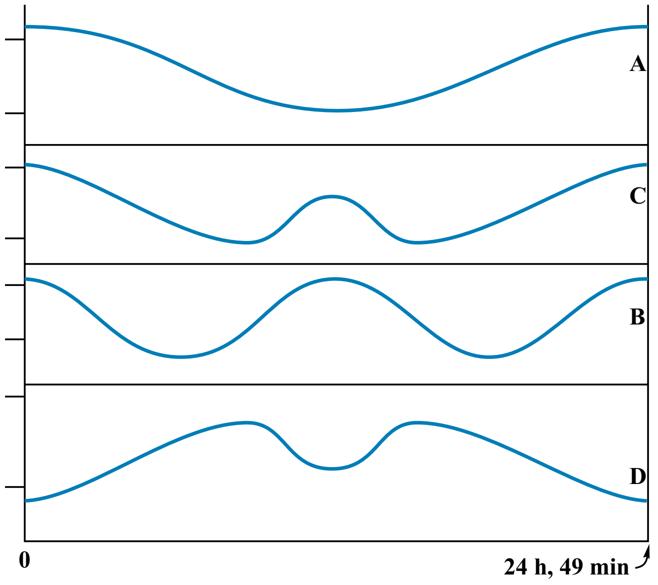


FIGURE 10-8 A simplified system with the moon and an ocean-covered Earth illustrates the principal feature of the tides. In this figure the continents are shown only to make it easier to identify Earth's orientation. (a) The angle of the moon's orbit with respect to the equator (the declination) oscillates regularly. The maximum declination is about 25°. (b) The tide bulges caused by the moon's tidal forces are shown here with the declination and size of the bulges greatly exaggerated, and the effects of the continents ignored. (c) Looking down from above the North Pole at the Earth and moon, we would see that the moon moves through a small segment of its orbit each time the Earth rotates. Hence, the moon is "overhead" at any point on Earth a little later each day. (d) In the simplified system depicted in (b), an observer at latitude A would see a diurnal tide, an observer at B would see a semidiurnal tide, and observers anywhere else on Earth, such as C and D, would see mixed tides. As discussed later in the chapter, the tides are more complex than shown in this figure.

the much simplified case of the moon at its maximum declination to see how diurnal, semidiurnal, and mixed tides might result (**Fig. 10-8b**).

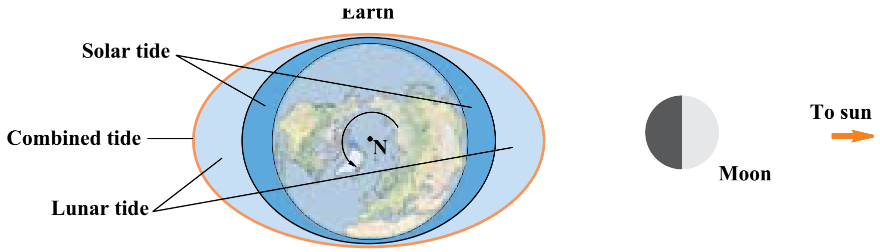
Imagine an observer standing at a point along latitude C in **Figure 10-8b** and rotating with the Earth. When the observer is at point C_1 there is a high tide. As the Earth rotates, the observer passes through the low tide at the back of the Earth (C_2) after the Earth has rotated a little more than 90°, or a little more than 6 h later. After 12 h and 24½ min, the observer passes a second high tide (C_3), but it is not as high as the original high tide. C_3 is further from AM than C_1 is from TM. Thus, as the bulge passes the longitude of this location (C_3), the highest point of the bulge is farther away from the observer than it was when the bulge passed the longitude of the observer's original position (C_1). The observer rotates farther with the Earth, passing a second low tide after about 18 h (C_4), and another high tide after 24 h and 49 min (C_1). The extra 49 min are due to the moon's progression in its orbit during the day (**Fig. 10-8c**).

We can follow the tidal patterns that would be observed at points A, B, and D in a similar way. A diurnal tide is observed at A, a semidiurnal tide at B, and mixed tides at C and D (**Fig. 10-8d**). Note that, in this simplified model of tides, pure semidiurnal tides occur only at the equator. Note also that, in mixed tides, low tides do not occur exactly midway between high tides.

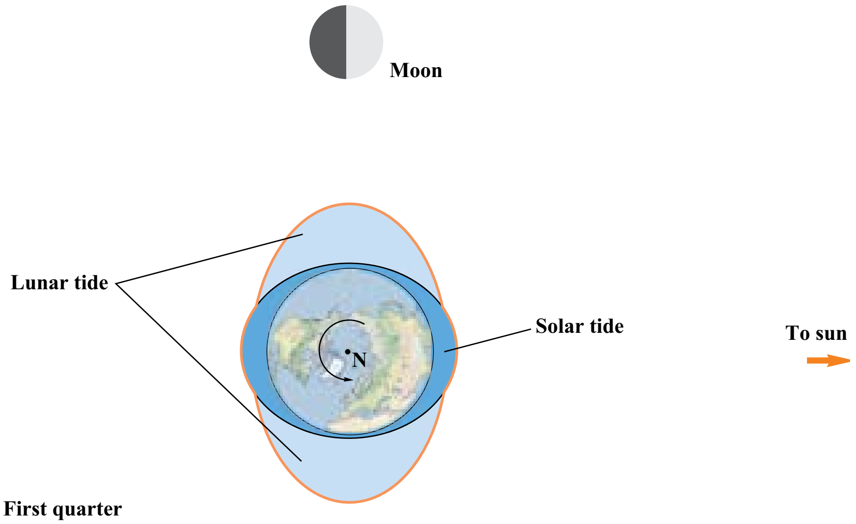
In the simple model shown in **Figure 10-8**, low tide would always be the same height at any specific location. However, the tide records in **Figures 10-5 and 10-7** show that this is not true. The reason is that the simplified system in **Figure 10-8** does not include solar tides that are added to lunar tides or the effects of continents both of which creates much greater complexity in the actual tides on the Earth.

The Origin of Spring and Neap Tides

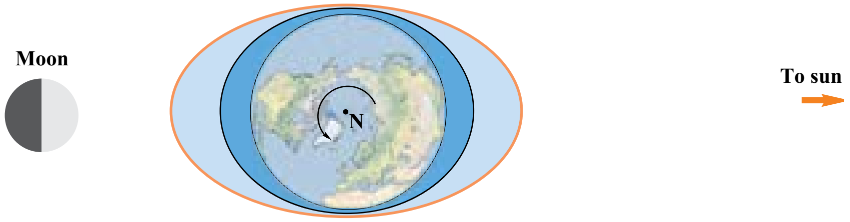
The sun exerts tidal forces on the Earth that are about half as strong as the lunar tidal forces. We can see how the solar and lunar tides interact by again considering a simplified ocean-covered Earth. Tide bulges are created by both the sun and the moon (**Fig. 10-9**). The tidal height at any point on our model Earth is the sum of the tidal heights of the lunar and solar tides. The moon's orbit around the Earth and the Earth's orbit around the sun are not quite in the same plane, but they are nearly so. We can ignore this small angle for now.



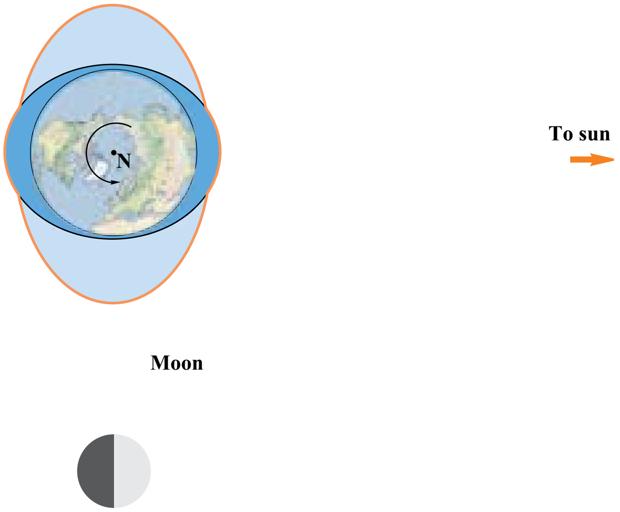
(a) New moon



(b) First quarter



(c) Full moon



(d) Third (last) quarter

FIGURE 10-9 A simplified depiction of the Earth–moon–sun system shows how the solar and lunar tides interact to create spring and neap tides. (a) At new moon, spring tides with a greater tidal range (higher high and lower low tides) occur because the tide bulges caused by the moon and the sun (both greatly exaggerated here) are aligned so that their maxima are at the same locations. (b) At first-quarter moon, neap tides occur because the moon's bulge and the sun's bulge are aligned at 90° to each other and the maxima of the moon's tide coincide with the minima of the sun's tide. (c) At full moon, spring tides occur again as the moon's and the sun's bulges are again aligned with their maxima at the same locations. (d) At fourth-quarter moon, neap tides occur again as the moon's and the sun's bulges are again aligned at 90° to each other and the maxima of the moon's tide coincide with the minima of the sun's tide. The observed spring and neap sequences on the Earth are more complicated for various reasons, including that the orbits of the moon and sun are not exactly in the same plane as this simplified figure depicts. These orbits are inclined to each other, and the inclination changes with time.

Figure 10-9a shows the relative positions of sun, moon, and Earth at a new moon. Because the entire disk of the moon is in shade as seen from the Earth, the moon must be between the sun and the Earth. Lunar eclipses occur when the three bodies are lined up precisely. When the alignment is not exact, we see the moon as a thin sliver of light. This is new moon. At new moon, we can see that the high-tide bulges of the solar and lunar tides are located at the same point on the Earth. The lunar high-tide bulge directly under the moon and the solar high-tide bulge directly under the sun combine in the same location, and the lunar and solar high tide bulges on the side of Earth directly away from the sun and moon also coincide. Finally, the locations on Earth where the low tide areas of the solar and lunar tide bulge also coincide. Thus, at new moon the solar and lunar high tides are added together and the solar and lunar low tides are added together, producing the maximum tidal range with the highest high tides and also the lowest low tides during the lunar month. These are spring tides.

Each day, the moon's movement in its orbit is the equivalent of the angle through which the Earth rotates in about 49 minutes. Approximately 7½ (7.38) days after full moon, the moon, Earth, and sun are aligned at right angles (**Fig. 10-9b**). The right half of the moon (as seen from the Northern Hemisphere) is now lit by the sun. The other part of the moon that is lit is hidden from an observer on the Earth. This is the moon's first quarter (The lunar month is counted from a new moon). At first-quarter moon, the lunar tide bulge coincides with the low-tide region of the solar tide, and vice versa. Because the tides are additive, the low tide of the solar tide partially offsets and reduces the height of the lunar high tide, and the high tide of the solar tide partially offsets the lunar low tide. The tidal range is therefore smaller than at full moon. These tides are the neap tides.

Fifteen days after new moon, the moon is directly between the Earth and the sun (**Fig. 10-9c**). Now the moon is entirely lit by the sun as seen from the Earth and there is a full moon. At full moon, the solar and lunar tide bulges again coincide and there is a second set of spring tides for the month. These tides are equal in height and range to the spring tides that occurred 15 days previously at new moon. Similarly, a little more than 22 days (22.14) after new moon, there is a third-quarter moon. The left side of the moon is lit for Northern Hemisphere observers (**Fig. 10-9d**). The solar and lunar tides again offset each other, and there is a second set of neap tides.

After about 29½ (29.53) days, the moon is new again, we have a new set of spring tides and begin a new lunar month. From this simple model, we can see why we have two sets of spring tides and two sets of neap tides in each 29½-day lunar month (**Fig. 10-8**).

Other Tidal Variations

From the simple model that we have been discussing, we have seen that the height of the tide due to the moon varies on a cycle that is 24 h 49 min long. High tides actually occur every 12 h 24½ min because there are two bulges. Similarly, the solar tide varies on a 24-h cycle, and high tides occur every 12 h. The motions of the moon and the Earth in their orbits are much more complex than the simple model suggests, and tidal variations occur on many other timescales. These additional variations are generally smaller than the daily or monthly variations, but they must be taken into account when precise tidal calculations are made. They are due to periodic changes in the distances between the Earth and the sun and between the Earth and the moon, and the various declinations. Declinations are the angles between the Earth's plane of orbit around the sun, the Earth's axis of spin, and the moon's orbital plane. **Table 10-1** lists some of the more important variations of Earth–moon–sun orbits, along with the periodicity of the **partial tides** that they cause.

TIDES IN THE EARTH'S OCEANS

Tides in the Earth's oceans behave somewhat differently from those on the hypothetical ocean-covered Earth. For example, on

TABLE 10-1 **Selected Tidal Components**

Tidal Component	*Period (h)*	*Relative Amplitude*	*Description*
SEMIDIURNAL			
Principal lunar	12-42	100.0	Rotation of Earth relative to moon
Principal solar	12-00	46.6	Rotation of Earth relative to sun
Larger lunar ecliptic	12-66	19.2	Variation in moon–Earth distance
Lunisolar semidiurnal	11.97	10-7	Changes in declination of sun and moon
DIURNAL			
Lunisolar diurnal	23.93	58.4	Changes in declination of sun and moon
Principal lunar diurnal	25.82	41.5	Rotation of Earth relative to moon
Principal solar diurnal	24.07	19.4	Rotation of Earth relative to sun
BIWEEKLY AND MONTHLY			
Lunar fortnightly	327.9	17.2	Moon's orbit declination variation from zero to maximum and back to zero
Lunar monthly	661.3	9.1	Time for moon–Earth distance to change from minimum to maximum and back
SEMIANNUAL AND ANNUAL			
Solar semiannual	4382.4 (182.6 days)	8.0	Time for sun's declination to change from zero to maximum and back to zero
Anomalistic year	8766.2 (365.2 days)	1.3	Time for Earth–sun distance to change from minimum to maximum and back

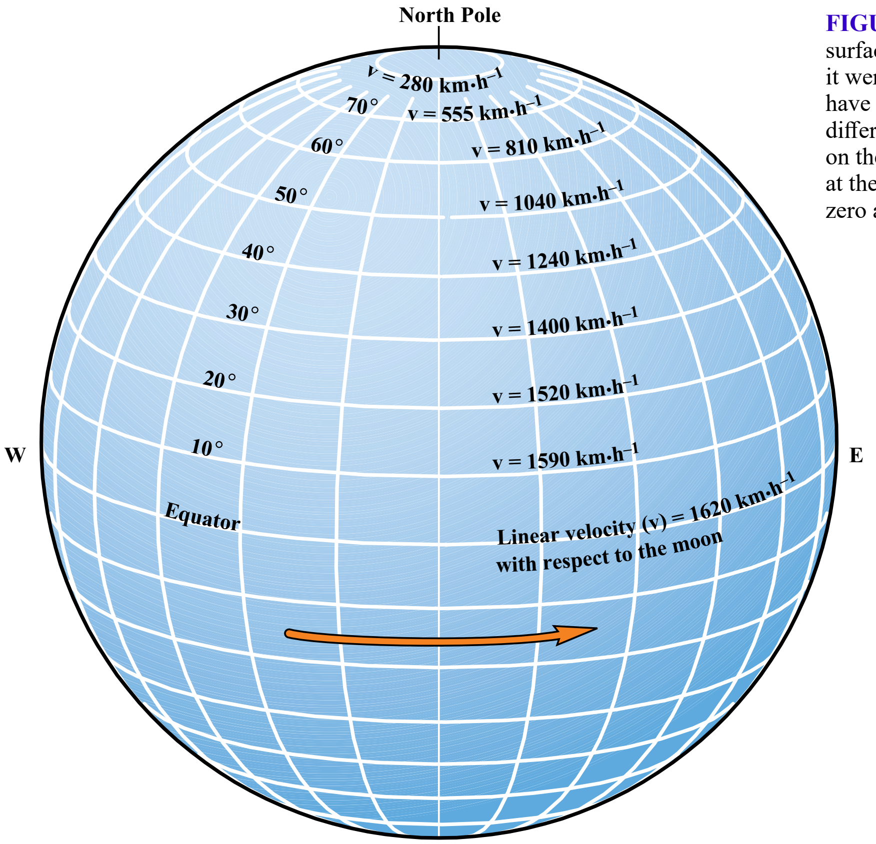


FIGURE 10-10 The tide wave must move across the Earth's surface as the Earth spins in relation to the moon and sun. If it were to do so exactly in time with the Earth's spin, it would have to move at different speeds across the Earth's surface at different latitudes. This is because the orbital velocity of points on the Earth's surface due to the Earth's spin is at a maximum at the equator and decreases with increasing latitude until it is zero at the poles.

the model Earth, pure semidiurnal tides would occur only at the equator (**Fig. 10-8**), except when the moon's declination was zero, and then all points on the Earth would have pure semidiurnal tides. However, on the real Earth semidiurnal tides occur at places other than the equator (**Figs. 10-5, 10-6, 10-7**).

Four major interrelated factors alter the Earth's tides from the equilibrium model: the Earth's landmasses, the shallow depth of the oceans in relation to the **wavelength** of tides, the latitudinal variation of **orbital velocity** due to the Earth's spin around its axis, and the **Coriolis effect** (**CC12**). When these factors are included in calculations of tides, the calculated tides are called "dynamic tides."

Effects of Continents and Ocean Depth

In discussing the factors that affect tidal motions, it is convenient to envision tide waves moving across the Earth's surface from east to west, even though, in fact, it is the Earth that is spinning. The peaks of the tide waves remain fixed in their orientation toward and away from the moon or sun, moving only slowly as the moon, Earth, and sun move in their orbits.

The presence of landmasses prevents the tide wave from traveling around the world. The continents are generally oriented north–south and bisect the oceans. The equilibrium tide wave moves from east to west. When the tide wave encounters a continent, its energy is dissipated or reflected, and the wave must be "restarted" on the other side of the continent. Because continents, landmasses, and the ocean basins are complicated in shape, the tide wave is dispersed, **refracted**, and reflected in a complex and variable way within each ocean basin.

The average depth of the oceans is about 4 km, and the maximum depth is only 11 km. In contrast, the wavelength of the tide wave is one-half of the Earth's circumference, or about 20,000 km at the equator. Hence, the water depth is always considerably less than 0.05 times the wavelength of the tide wave (that is, the water depth is considerably less than *L*/20), and the tide wave acts as a **shallow-water wave** (**Chap. 9**). The speed of a shallow-water wave is controlled only by the water depth. In the average depth of the oceans (4 km), the tide **wave speed** is approximately 700 km·h–1. The equilibrium model tide wave always travels across the Earth's surface aligned with the movements of the moon and sun. However, to travel across the Earth's surface and remain always exactly lined up with the moon (or sun), the tide wave would have to travel at the same speed as the Earth's spin. At the equator, the wave would have to travel at about 1620 km·h–1. Because it is a shallow-water wave that can travel at only 700 km·h–1, the tide wave at the equator must lag behind the moon as the moon moves across the Earth's surface.

The interaction between the moving tide wave that lags behind the moon's orbital movement and the tendency for a new tide wave to be formed ahead of the lagging wave is complex. However, the result is that the tide wave lags behind the moon's orbital movement, but not by as much as it would if it were not continuously re-created. The tide wave is said to be a forced wave because it is forced to move faster than an ideal shallow-water wave.

Because the tide wave is a shallow-water wave and its speed depends on the water depth, the tide wave is refracted in the same way that shallow-water wind waves are refracted as they enter shallow water. Dynamic-tide theory therefore must include the refraction patterns created by the passage of tide waves over **oceanic ridges**, **trenches**, shallow **continental shelves**, and other large features of the ocean basins.

Latitudinal Variation of the Earth's Spin Velocity

The tidal time lag changes with **latitude** because the orbital velocity (due to the Earth's spin) of points on the Earth's surface decreases with latitude (**Fig. 10-10**). At latitudes above about

65°, the shallow-water wave speed is equal to or greater than the orbital velocity. Hence, there is no tidal time lag at these latitudes, and the tide wave even tends to run ahead of the moon's orbital movement. Another complication in calculating the tide wave time lag is the fact that the Earth's axis is usually tilted in relation to the moon's orbit (and to the Earth's orbit with the sun). Therefore, even on a planet with no continents, the tide waves would not normally travel exactly east–west.

Coriolis Effect and Amphidromic Systems

Tide waves are shallow-water waves in which water particles move in extremely flattened elliptical orbits. In fact, the orbits are so flattened that we can consider the water movements to be horizontal. Water moving within a tide wave is subject to the Coriolis effect (CC12). One important consequence of the Coriolis deflection of tide waves is that a unique form of **standing wave** can be created in an ocean basin of the correct dimensions. This type of standing wave is called an **amphidromic system,** in which the high- and low-tide points (the wave **crest** and **trough**, respectively) move around the basin in a rotary path—counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

Figure 10-11 shows how an amphidromic system is established in a wide Northern Hemisphere basin. In the Northern Hemisphere, a standing-wave crest (**antinode**) enters the basin at its east side. As water flows westward, it is deflected ***cum sole*** to the north, causing a sea surface elevation on the north side of the basin as the wave height at the east boundary decreases behind the crest. Water now flows toward the south with the north-to-south pressure gradient created by the sea surface elevation on the north side of the basin. As water flows south, it is deflected

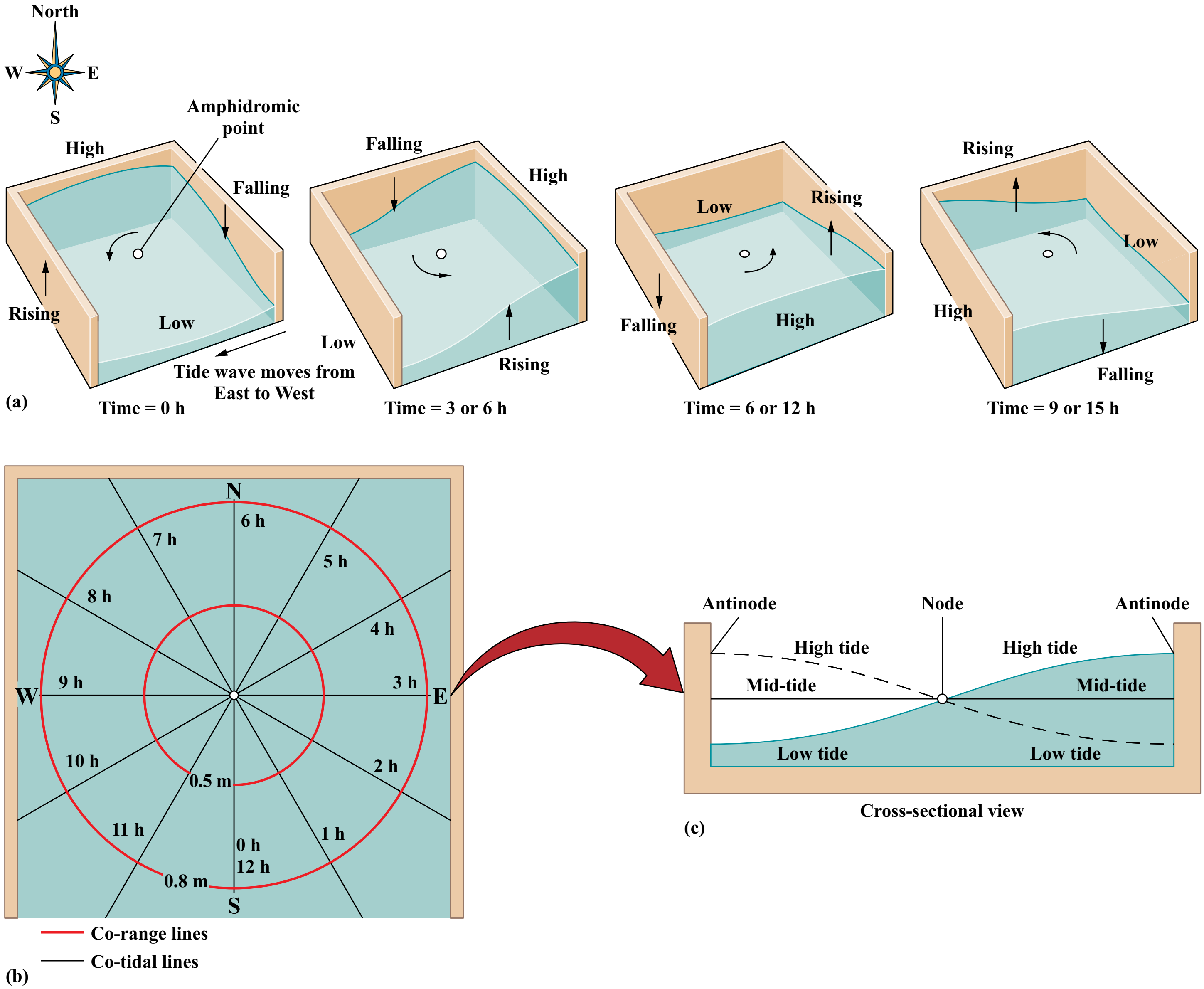
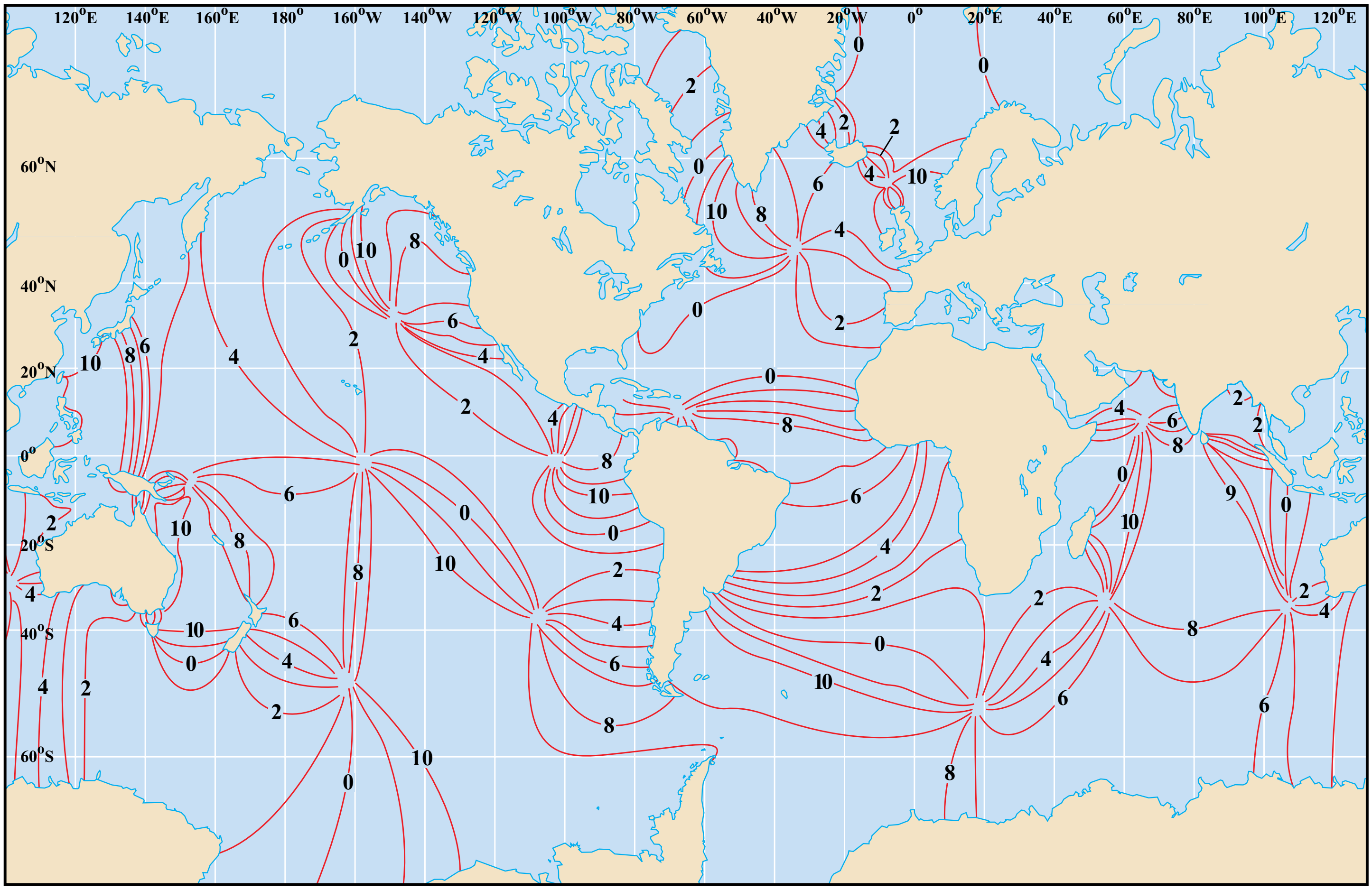


FIGURE 10-11 Development of an amphidromic standing-wave oscillation in response to the Coriolis effect in the Northern Hemisphere. (a) An amphidromic system is created in the principal solar semidiurnal or diurnal component of the tide when the tide wave enters a basin and is deflected by the Coriolis effect so that it rotates around the basin and returns to the entrance exactly 12 or 24 h later. (b) In an idealized Northern Hemisphere amphidromic system, the tidal range is the same for all places on any circle centered on the amphidromic point. The line along which the low tide or high tide is located progresses around the basin counterclockwise (clockwise in the Southern Hemisphere). In this plan view, high tide or low tide occurs along each of the radial lines at the indicated number of hours after occurring along the line labeled "0 h". (c) A cross-sectional view of the basin shows the up-and-down motion about the node upon which the rotation around the basin is superimposed

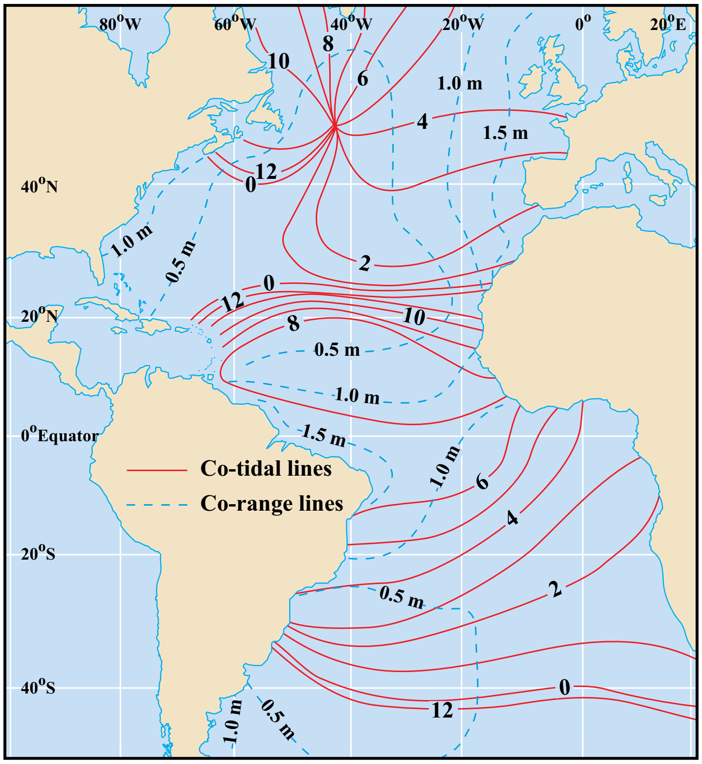


Mercator projection

FIGURE 10-12 Amphidromic systems of the principal lunar semidiurnal tidal component in the Earth's oceans. The lines show the location of the tidal maximum. The numbers indicate the number of hours that elapse as the maximum tide (crest) travels from the line labeled 0 to the indicated line. Notice that the crest of the tide wave moves in rotary amphidromic systems in most of the ocean basins, and that the rotation is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Because it is a shallow-water wave, the tide wave is also refracted as water depth changes, resulting in some of the complex bending of the wave in certain parts of the oceans.

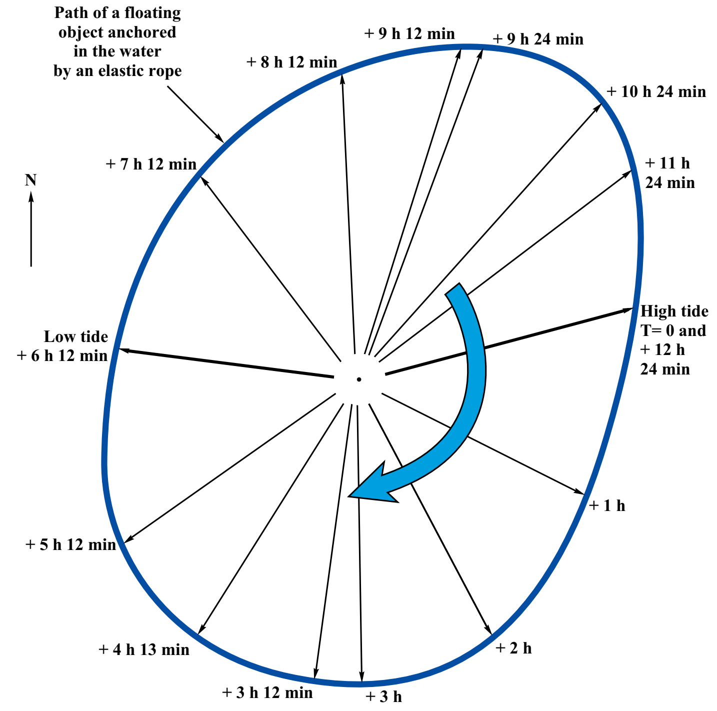
cum sole to the west. The sea surface elevation continues to move around the basin counterclockwise in this way until it returns to the east side of the basin. If the standing-wave crest returns to the east side of the basin after exactly 12 h and 24^1/2 min (or any multiple thereof), it will meet the crest of the next lunar tide wave and the oscillation is then said to be **tuned**.

One important characteristic of amphidromic systems is the amphidromic point (**node**) near the center of the basin, at which the tidal range is zero (Fig. 10-11). Amphidromic systems are established in all the ocean basins (Fig. 10-12). However, different amphidromic systems are set up for each tidal component (Table 10-1) because the components have different wavelengths. Hence, a location in an ocean basin that is an amphidromic point for one component of the tide will have a zero tidal range for that component, but will have tides generated by tidal components with other periods. In addition, some basins tune more easily with a particular tidal component. In parts of such basins, the tidal

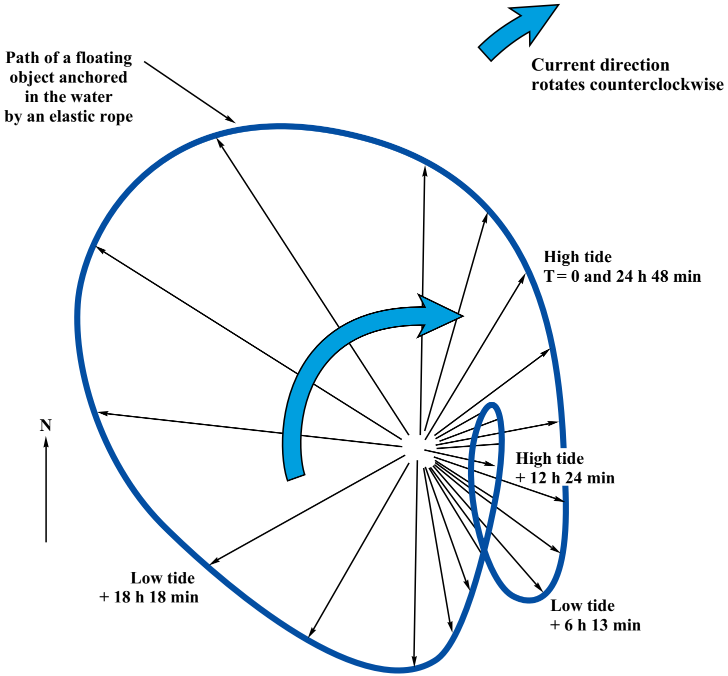


Mercator projection

FIGURE 10-13 (Right) The principal lunar tidal component wave enters the Atlantic Ocean from the Indian Ocean around Antarctica and travels north into the North Atlantic, where it forms an amphidromic wave. Red lines show the location of the tidal maximum. Dashed blue lines are contours of tidal range. Note the higher tidal range on the west side of the South Atlantic compared to the east side. Also note that the tidal range increases in all directions from the center of the amphidromic system.



(a) Semidiurnal tide



(b) Mixed tide

FIGURE 10-14 Changes in the direction and magnitude of open-ocean tidal currents in the Northern Hemisphere. The arrows indicate the direction of the current at approximately hourly intervals, and the length of the arrows is proportional to the current speed. The outer blue line describes how an object would move in the water if there were no currents or water movements other than tidal currents. (a) Where there is a simple semidiurnal tide, the current speed varies little, but its direction rotates clockwise through 360° every 12 h 24½ min. (b) Where there is a mixed tide, the variations of current speed and direction can be more complex. In this case, the current direction rotates clockwise twice within 24 h 49 min, but the rate of rotation and the current speeds follow very different patterns within the two successive 12-h periods.

range due to that tidal component can be enhanced in relation to the ranges due to other components. This effect explains the presence of dominant diurnal and semidiurnal tides at many locations where they would not be predicted by equilibrium tide theory.

TIDES IN THE OPEN OCEANS

Having examined the many factors that control tides, we can now look at some characteristics of real tides in the ocean basins. Much of what we know about the behavior of the tides is based on tidal-height measurements made along the coasts and on islands. The details of tidal movements in the deep oceans generally are derived from these measurements and dynamic-tide theory, although a number of deep-sea tide gauges have been deployed to make direct observations during the past several decades. Satellites, moored current meter arrays and AUVs now also provide data that is helping to steadily refine our understanding of deep-ocean tidal motions.

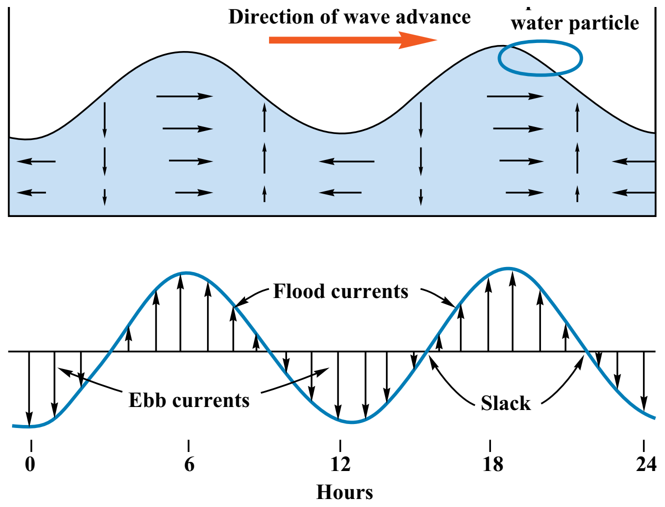
Figure 10-13 shows the progression and height of the principal lunar semidiurnal component of Atlantic Ocean tides. This component is only one of the many different partial tides that must be added to determine tidal height at any time and location.

The most striking feature of **Figure 10-13** is that the tide wave does not move from east to west with the moon, as equilibrium tide theory predicts. This is because the Atlantic Ocean is a relatively narrow basin in which only a small tide wave can be generated during a single pass of the moon. The small east–west tide wave soon encounters the American continent, where it is partially reflected and much of its energy is dissipated.

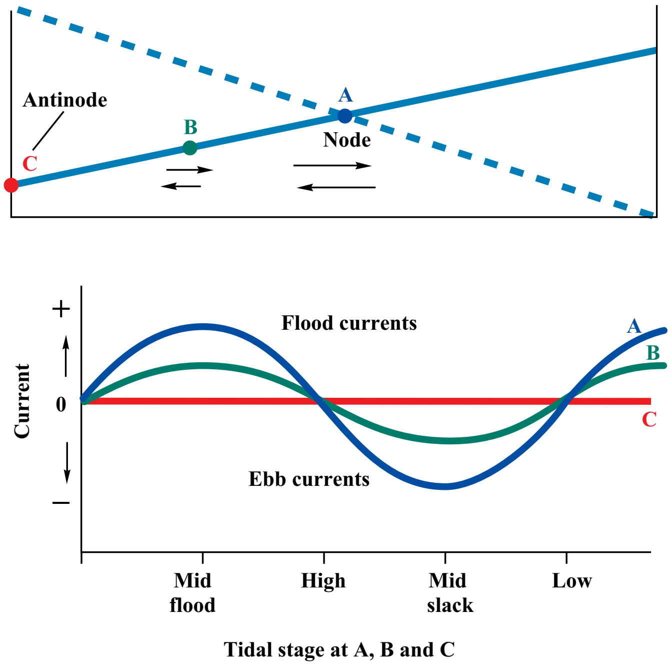
The only segment of the Earth where the tide wave can travel east to west around the world without encountering a landmass is near Antarctica. At this high latitude, the orbital velocity of the Earth's surface is low enough (**Fig. 10-10**) that the shallow-water tide wave can travel fast enough to keep up with the moon's orbital movement. The tide wave around Antarctica is therefore well developed (**Fig. 10-12**). It enters the Atlantic Ocean between the tip of South Africa and Antarctica and is partially deflected and dispersed into the South Atlantic Ocean. The tide wave moves northward through the South Atlantic Ocean as a progressive wave. As it travels north, it interacts with the weaker east–west wave formed in the Atlantic and is reflected and refracted in complex ways. It is also deflected by the Coriolis effect. Although the deflection is obscured by other factors in the southern part of the South Atlantic, it causes tides to be slightly higher on the South American coast north of Rio de Janeiro than on the opposite African coast (deflection to the left in the Southern Hemisphere). The Coriolis deflection is also partially responsible for tides being slightly higher on the coasts of Europe and North Africa than on the North American coast (deflection to the right in the Northern Hemisphere).

In the North Atlantic, the progressive wave traveling north from Antarctica is converted into the standing wave of an amphidromic system (**Fig. 10-13**). The high tide moves around the North Atlantic basin counterclockwise and arrives back where the next crest of the Antarctic progressive wave arrives almost exactly 12 h and 24½ min later. The North Atlantic Ocean basin is therefore well tuned to the semidiurnal tidal component, and this component dominates and produces semidiurnal tides in this region (**Fig. 10-6**).

Amphidromic systems similar to the system in the North



(a) Progressive wave



(b) Standing wave

FIGURE 10-15 Tidal currents. (a) In a pure progressive wave, the forward motion in the wave is at a maximum as the crest passes, and in the opposite direction when the trough passes. Thus, if the tide wave were a pure progressive wave, the flood currents would reach a maximum at high tide and the ebb currents would reach a maximum at low tide. (b) In a standing wave, the horizontal currents are always zero at the antinodes, and they are reversing currents whose maximum speed increases from zero at the antinode to a maximum at the node. The maximum current speeds are reached at mid flood and mid ebb. Because most tides have both progressive-wave and standing-wave components, there is no fixed relationship between the times of high and low tide and the times of maximum tidal current and slack water at different locations. Tidal currents are also complicated by seafloor friction.

Atlantic are also present in the North Sea and the English Channel. However, the Gulf of Mexico has a natural period of about 24 h. Therefore, the semidiurnal tidal component in the Gulf of Mexico is poorly developed, and the diurnal component is stronger, so diurnal tides dominate in some parts of the Gulf (**Fig. 10-6**). The Pacific Ocean basin is wider than the Atlantic Ocean basin. Therefore, the Pacific has a more developed east–west tide wave and greater complexity than the Atlantic Ocean. In both the Pacific Ocean and the Caribbean Sea, diurnal and semidiurnal tide waves are relatively well tuned and tides are generally mixed tides.

TIDAL CURRENTS

Orbits of water particles in tide waves are so flattened that water movements in the tide wave are essentially oscillating currents. The magnitude and periodicity of these currents are as important to mariners as the tidal range is, particularly in coastal and estuarine regions. Although tidal currents are relatively weak in the open oceans, their speed increases as the tide wave moves inshore and its energy is compressed into a shallower depth of water. Tidal-current speed also increases where the tide wave must move large quantities of water through a narrow opening into a large bay or estuary, such as the entrances to San Francisco Bay and New York Harbor.

Open-Ocean Tidal Currents

Tidal currents are generally weak and rotary in character in deep-water areas away from the coast in the large ocean basins (**Fig. 10-14**). In areas of the Northern Hemisphere with semidiurnal tides, the tidal-current direction rotates progressively, usually clockwise, and completes a 360° rotation in 12 h 24½ min (**Fig. 10-14a**). The current speed varies but is never zero.

In areas with mixed tides, the progression of tidal-current speed and direction is more complicated (**Fig. 10-14b**) because both variables represent a combination of two different tidal components. Note that the times of maximum and minimum tidal-current speed are apparently not related to the times of high and low tide.

Tidal currents flow at all depths in the oceans. While current speeds due to tides in the deeper parts of the oceans are slow, these currents interact with the topography of the seafloor in complex ways. Although little is know about these interactions, it is known that increased turbulence as tidal currents flow over seafloor topography is a significant factor in vertical mixing of water masses.

Temporal Variation of Tidal-Current Speeds

Many people mistakenly believe that the tidal currents will stop when the tide reaches its highest and lowest points. This is rarely true. In fact, if the tide were a pure progressive wave, the tidal current would be at its fastest at high or low water. We can see why by considering the motions of water particles in the tide wave (**Fig. 10-15a**). However, the maximum tidal currents rarely coincide with high or low tide for several reasons. The most important is that all tides are complex combinations of many components. Some components may be progressive waves, some may be standing waves, and some may have both progressive-wave and standing-wave characteristics. In addition, tide waves are reflected and refracted, so the observed tide may be the result of several different waves moving in different directions.

In a standing wave, currents are at their maximum midway between high and low tide, when the sea surface is exactly level (**Fig. 10-15b**) Current speed varies not only with time, but also with location in the wave. It is highest at the node and is always zero at the antinodes, where the vertical water surface displacement, or tidal range, is greatest.

In most places, the tide is a complex mixture of progressive-wave and standing-wave components that vary from location to location. Hence, the relationship between the timing of **slack**

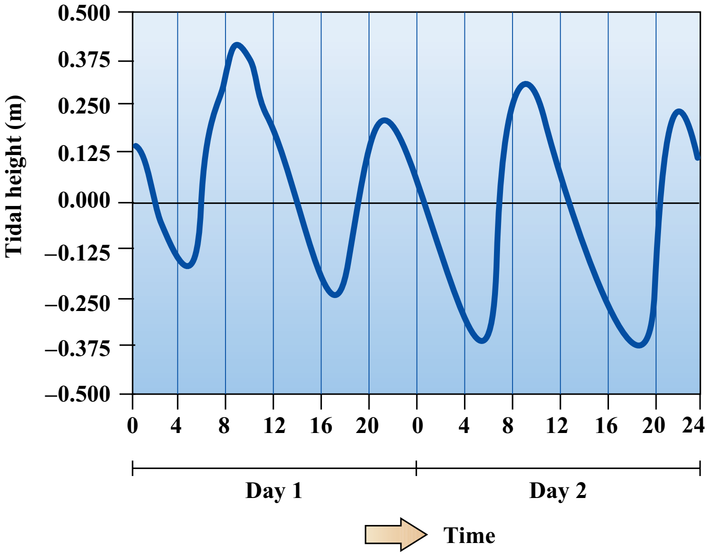


FIGURE 10-16 This tidal-height plot for the Hudson River near Albany, New York (about 220 km from New York Harbor), shows that the tide rises much faster (that is, the plot is steeper) than it falls

water (or, conversely, maximum current) and high and low tide is different for each location. Curiously, at certain times, some locations have tidal currents but no tide (zero tidal range), and other locations have a large tidal range but no tidal currents. We can envision such locations to be the node and antinode, respectively, of a standing wave that is the dominant component of the tides in that location, although the situation is generally more complicated because the tide is the sum of many different components of both solar and lunar tides.

Tide tables that list only times of high and low tide are useless for determining tidal-current speeds because there is no consistent relationship between the times of high and low water and the times of highest current speed and slack water. The only generalization that can be made about the tidal currents is that their maximum speed will increase or decrease as tidal range increases or decreases from day to day. Therefore, tidal currents must be measured in each location for which a forecast of the current speed is important, just as tidal ranges must be measured. Tidal-current information from such measurements is subject to **harmonic analysis** that is similar to the analysis of tidal-height data described later in this chapter. From this analysis, tidal-current tables are produced.

Tidal Currents in Estuaries and Rivers

Tides extend far into many bays, estuaries, and rivers. Tides in such locations are affected by the extremely shallow water depths, freshwater flow, and friction with the seafloor. In very shallow water, the crest of the tide wave moves in significantly deeper water than the trough. Therefore, the high tide tends to catch up to the low tide in estuaries or rivers where the tide travels long distances through shallow water. As a result, river tides can be modified so that there is a long period between high and low tide, but a very short period between low and high (**Fig. 10-16**).

In some areas where tidal ranges are large and the tide enters a channel or bay that narrows markedly or has a steeply sloping seafloor, tidal bores may occur. A tidal bore is created when the currents in the flooding tide are faster than the speed of a shallow-water wave in that depth. The leading edge of the tide wave must force its way upstream faster than the wave motion can accommodate. The wave therefore moves up the bay or estuary as a wall of water, much like a continuously breaking wave (**Fig. 10-17**). Well-known tidal bores occur in the Bay of Fundy in Nova Scotia and in Turnagain Arm off Cook Inlet in Alaska. Most tidal bores are less than 1 m high, but they can reach as much as 10 times that height. Some bores, notably one in China, are high enough that they attract surfers who are looking for the longest ride of their lives.

FIGURE 10-17 Tidal bore in a channel of the Kent River near Arnside, Westmoreland, England

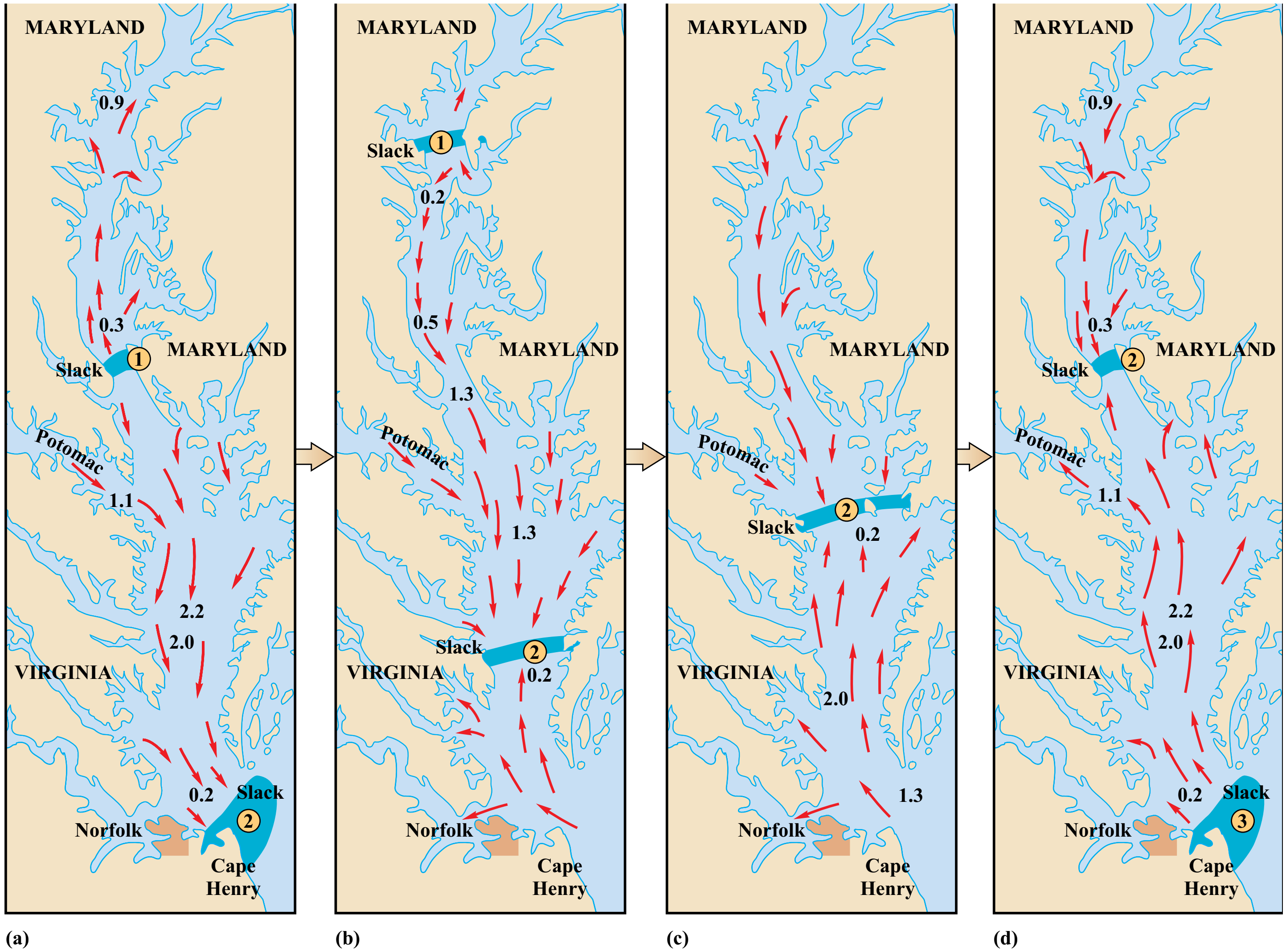


FIGURE 10-18 (Above) Chesapeake Bay has a primarily progressive-wave tide. The tide wave enters the estuary and moves progressively up the bay, reaching the north end about 10 h after entering the bay. Follow the successive slack-water occurrences numbered 1, 2, and 3 in these diagrams as they move north. (a) Slack water occurs at the mouth of the bay just as the flood begins and also at a location just above mid bay. (b) Two hours after the start of the flood, the two areas of slack water have migrated northward. (c) Four hours after the start of the flood, the northernmost slack has reached the north end of the bay and the second slack is almost in mid bay. (d) Six hours after the start of the flood, the slack that entered the bay 6 h earlier is now where its preceding slack had been at that time, and a new slack-water area occurs at the mouth of the bay as the ebb begins.

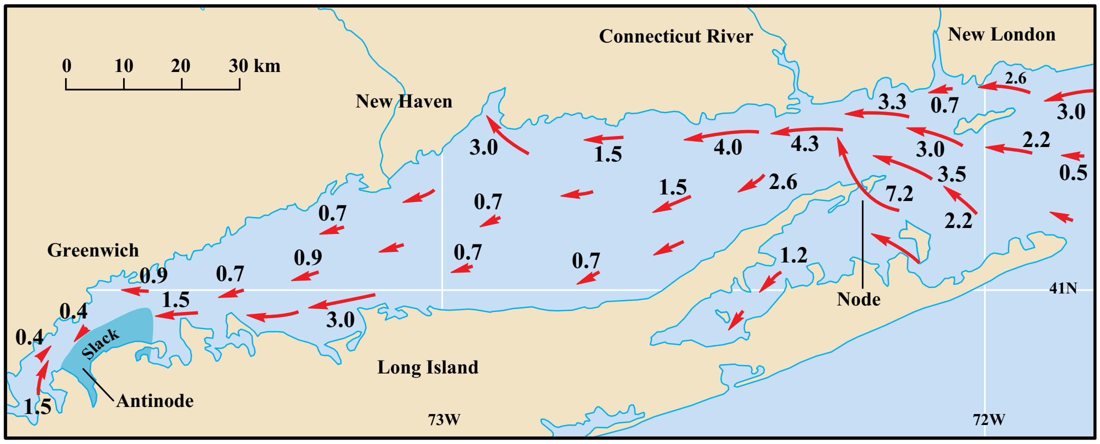


FIGURE 10-19 (Right) Long Island Sound has a predominantly standing-wave tide, with a node at the entrance to the sound and an antinode at the western end. There is little or no tidal current at any time during the tidal cycle at the western end where the antinode is located. In the remainder of the sound there are reversing tidal currents, with the maximum current speed increasing from the western end to the eastern opening to the ocean, where a node occurs

The tidal currents in estuaries and rivers are affected by freshwater flow. Freshwater flowing into a river or estuary prolongs the ebb tide in relation to the flood tide because more water must be transported out of the river during the ebb than enters during the flood to accommodate the freshwater discharge. River flow rates can substantially change the nature of tides and tidal currents in estuaries. Accordingly, tide tables and tidal-current tables for bays, estuaries, and rivers must be used only as a general guide, particularly when river flow rates are abnormally high or low.

Tidal currents within bays, rivers, and estuaries can behave as progressive waves, standing waves, or, in some cases, a combination of the two. In long bays with progressive tides, tidal currents can flow in opposite directions at the same time in different sections of the bay. Chesapeake Bay has this type of circulation (**Fig. 10-18**). Slack water from each tide migrates up the bay about 60 km each hour and takes about 10 h to travel the length of the bay. Successive slack tides enter the bay approximately every 6 h 12 min because each semidiurnal tide has slack water associated with both flood and ebb. This progressive wave is not modified significantly by an east–west wave, because the bay is too narrow for a significant wave to be generated directly by the tide-generating forces.

Tidal currents in Chesapeake Bay are somewhat more complex than those shown in **Figure 10-18** because the bay does not have uniform depth. The tide wave is slowed more rapidly at the sides of the bay, where the water is shallower and friction with the channel sides is enhanced. In this and other bays with a deep central channel and shallower sides, the tidal current reverses sooner at the sides than in the deep channel. This effect can be useful to boaters who want to avoid the fastest opposing currents. It is also a mechanism for mixing water from the deep main channel with water from the shallow sides, and therefore is of interest in studies of the dilution of discharges.

Long Island Sound has a predominantly standing-wave tide (**Fig. 10-19**). Tidal currents first flow westward throughout the length of the sound, then slack water occurs throughout the sound, and subsequently the current reverses and flows eastward throughout the sound. The area of nearly permanent slack water at the west end of the sound is the standing wave antinode and has a large tidal range, but little or no tidal current. The east end of the sound is the node and has a small tidal range.

TIDE PREDICTION

As we have seen, the dynamic-tide theory must take into account many different variables to predict tidal height at any given location at a specific time. The best predictions made by applying dynamic-tide theory closely approximate the actual tides. However, the predictions are not accurate enough for use by mariners, particularly in complex estuaries and bays. Therefore, tide predictions are made from tide observations. Tidal variations are observed and recorded continuously at many locations throughout the globe. Reasonably accurate tide predictions can be made from a tide record covering only a few months, but much longer records produce more accurate predictions.

Once the tide record is available, computers may be used to perform harmonic analysis of the data to identify components of the complex wave. For example, harmonic analyses would distinguish the five component waves in **Figure 9.12b** from the complex wave record in **Figure 9.12a**. Harmonic analysis determines the wave heights and time lags (in relation to the moon's orbital movement or other motions) of each of the many different tidal components (**Table 10-1**). More than 390 different tidal components have been identified. Once the timing, periodicity, and **amplitude** of each component have been determined for a particular location, computing the magnitude of each component for any point in time in the future is relatively easy. Simple addition of the components gives the tidal height at the future time and location.

Tide predictions made in this way are used extensively. They are the basis for the tide predictions published daily in many newspapers and the printed tide tables offered in bait-and-tackle stores, dive shops, and marinas.

Satellite-based radar sensors accurate enough to measure tidal heights have allowed detailed mapping of the tides in the open-ocean areas where few tidal-height measurements had previously been made. The comprehensive tidal-height data sets collected through satellites are steadily accumulating and will eventually allow extremely accurate computer models of the tides.

Tidal currents vary locally, and predictions must be based on at least several months of current measurements at each specific location. Unfortunately, data for one location is inadequate to allow predictions to be made for other locations especially within complex estuaries.

MARINE SPECIES AND THE RHYTHM OF THE TIDES

Tides play an important role in the life cycles of many marine species. The most obvious connection is with species that live in the **intertidal zone**, for which the movements of the tides mean that they and their **habitats** are exposed to the atmosphere for variable periods during the day. These species have developed strategies to avoid dehydration and/or being eaten by birds and other predators during the times when their habitat is exposed to the air. For example, most species that live in sandy or muddy intertidal **environments** bury themselves in the sand when the tide is out. Many species that live on rocky shores have shells to retreat into or leathery outer skins that, in addition to deterring predators, resist loss of water through evaporation

Although we are only just beginning to learn about many of the subtle influences of tidal motions on marine species, there are numerous well-documented connections between the tides and the reproductive behavior of many species, especially with regard to the timing of the reproductive cycle. For example, many species that **spawn** eggs and **larvae** into the water column have spawning behavior that is timed to benefit the survival of the species. One example of this is that many **coral** species spawn en masse at a specific phase of the lunar tide, most often 1 or 2 days after a full moon in the spring months, when the tidal range is at its greatest. Spawning at this time ensures the greatest possible dispersal of the eggs and larvae to potential new sites for colonization. Spawning strategies are discussed in more detail in **Chapter 14**.

There is one connection between tides and species' reproductive strategies that you may be able to see for yourself. This is the use of high spring tides by some species at a certain time of year to place fertilized eggs in the sand high up on a **beach** where they cannot be reached by most predators that live in the water. Perhaps the best-known examples are sea turtles that haul themselves high up the beach, usually at night when there is a high spring tide, dig a hole in the sand, lay and bury their eggs, and then leave the eggs to hatch some weeks later. Many other species use a very similar strategy. Some of these species can be seen on beaches or mudflats around North America. For example, on the Atlantic coast, horseshoe crabs (*Limulus polyphemus*) spawn on the beaches between the high- and low-tide lines on nights when the spring high tide occurs. Female horseshoe crabs crawl out of the water as the tide advances, dig a cavity about 15 cm deep in the sand, and deposit several thousand large, greenish eggs. The male, which is attached to the female's back, fertilizes the eggs, and the eggs are then buried by sand moved by the advancing tide. The eggs hatch 14 days later when the next high spring tide covers the sand.

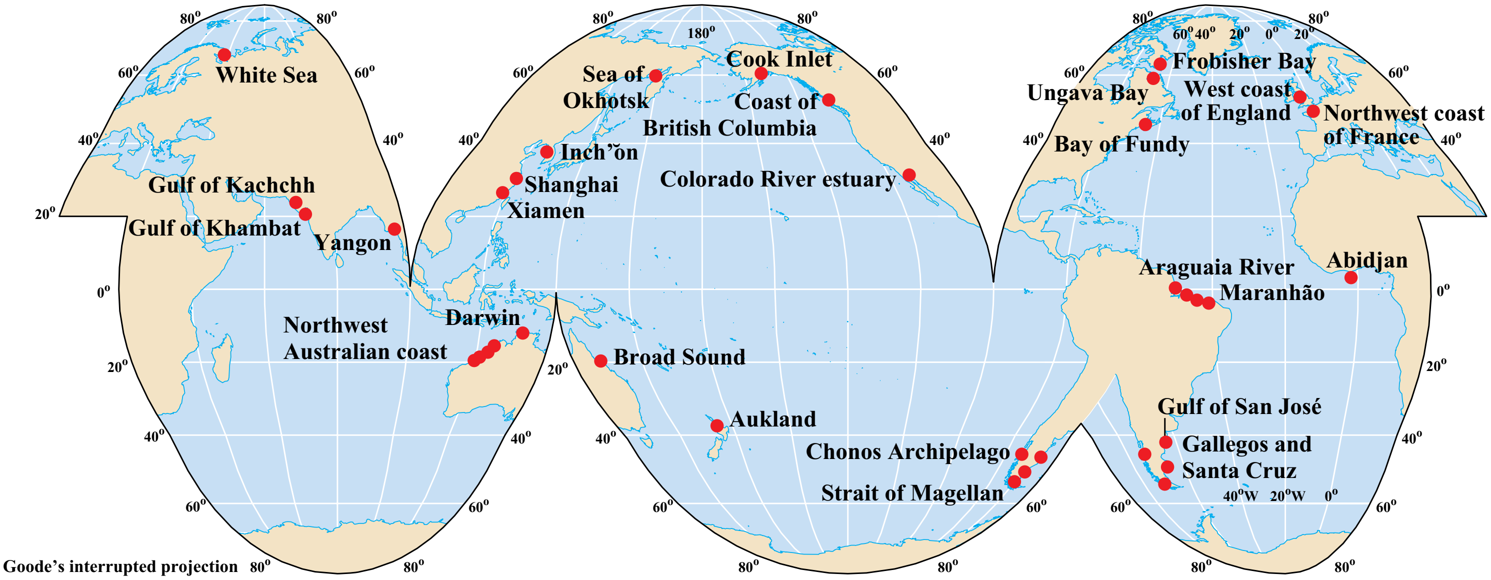


FIGURE 10-20 There are relatively few locations with a tidal range sufficiently large (more than about 5 m) that large scale tidal power-generating plants are considered to be feasible.

On the Pacific coast, several fishes use a similar strategy. The most famous of these fish species is the grunion (*Leuresthes tenuis*). This small, silvery fish comes completely out of the water onto the southern California and Baja beaches to spawn just after each maximum nighttime spring tide during March through September. The eggs are protected from wave action for the next 14 days because they are laid above the lower high-tide lines that occur at high tide between one spring tide and the next. Although they mature in about 9 days, the eggs do not hatch until they are disturbed by water and the wave **turbulence** that occurs as the next spring high tide occurs 14 days after they were laid. The eggs hatch within minutes of being exposed to the water.

Although the grunion is the most famous fish that spawns on the beach at high tide, other species also use this strategy, but they do not come completely out of the water to do so. One example of such a species is another small fish, the **surf** smelt (*Hypomesus pretiosus*), which spawns at high tides on the beaches of Puget Sound. Ask your instructor or do some research at your local library for information on species that might spawn on beaches near you.

ENERGY FROM THE TIDES

The tides are a potential source of inexhaustible and clean energy. Tidal energy is dissipated as heat by friction between **water masses** and the seafloor. Some of the energy can be captured by electricity-generating turbines placed in locations where tidal currents are very fast. However, very few locations have maximum tidal currents that are fast enough to drive turbines efficiently. Even where tidal currents are swift, they generally need to be enhanced by the tidal flow being channeled into the turbines through narrow openings. The best locations for capturing tidal energy are bays or estuaries with a large tidal range and swift tidal currents and where a dam can be built across the entrance. The dam is constructed with a number of narrow openings in which turbines are located. Water entering the bay

FIGURE 10-21 (Right) La Rance tidal power-generating plant in France.

is channeled through the turbines as the tide enters the bay, and again as the tide flows back out of the bay.

For a tidal power-generating plant of this type to be feasible, the tidal range needs to exceed about 5 m, and it must be possible to build a dam that isolates an area into which such a tide flows from the open ocean. The most promising locations are few and widely distributed (**Fig. 10-20**). A large tidal power-generating plant has operated successfully at La Rance in France since the 1960s (**Fig. 10-21**). There has been continuing interest in constructing other plants, notably in the Bay of Fundy, Nova Scotia. Such projects have a number of problems, two of which are especially important.

First, a tidal power-generating plant cannot generate energy throughout the 24 h in a day. Power cannot be generated during the period of slack water when tidal currents are low. Judicious operation can retain water outside or behind a dam to some extent and thus lengthen the period during which power can be generated, but generating power uniformly over a 24-h period is apparently not possible.

The second problem is that building a dam across a bay substantially alters the **ecology** and other aspects of the bay. For example, the Bay of Fundy sustains rich and **diverse** marine **communities** and fisheries and has a famous tidal bore. Building a dam across the mouth of the bay would drastically alter or destroy both the fishery and the tidal bore. Fishers who live around the bay would lose both their local catch and access to the open ocean for their boats. Tourism would decline with the loss of the tidal bore. The benefits and losses associated with tidal power-generating stations that use dams to close off arms of the sea will be difficult to balance. A decision to build or not build such a plant at the Bay of Fundy (or anywhere else) will be controversial and will generate opposing views from reasonable people.

As an alternative to tidal power plants that rely on dams, submerged turbines can be deployed, preferably in a location where the tide wave is restricted and becomes a reversing rather than rotary current. Some such tidal power plants have been tested and deployed but they generate limited amounts of power and do not generate power consistently at times of day when it is needed. Therefore, as with several renewable energy option, efforts are being made to produce power storage capabilities to use with such installations.

While tidal power potentially available from the oceans is very large, its real potential for the foreseeable future is, like wave energy, believed to be small and the technology is most suited to use in specific local situations.

CHAPTER SUMMARY

Tide-Generating Force.

Bodies orbiting together do so around their common center of mass. A centripetal force acting toward the other body is needed to keep each body in orbit. This force is supplied by the gravitational attraction between the bodies. The centripetal force needed to maintain the Earth in its common orbit with the moon (or sun) is the same at all points within the Earth. However, the gravitational force of the moon (or sun) is inversely proportional to the distance from the moon's (or sun's) center of mass. The gravitational force exerted by the moon (or sun) is therefore slightly higher on the side of the Earth facing the moon (or sun) than on the other side. Hence, there is a slight excess of gravitational force over centripetal force at the Earth's surface facing the moon (or sun), and a slight excess of centripetal force over gravitational force at the opposite side of the Earth. The slight imbalances are the tide-generating forces. Tide generating forces exerted by the sun are only 46% as strong as those exerted by the moon because even though the sun is more massive than the moon, it is much farther away from the Earth than the moon is.

Characteristics of Tides.

Tides resemble patterns of oscillating sea surface elevation caused by simple progressive waves or by the addition of two or more progressive waves. Because the moon's orbit is inclined to the equator, tides are usually predominantly one of three types. Diurnal tides have one high and one low tide per tidal day (24 h 49 min). Semidiurnal tides have two high and two low tides each tidal day, and the two lows (and two highs) are of equal height. Mixed tides have two high and two low tides each tidal day, but the two lows (and two highs) are not of equal height. Tidal range varies with location and from day to day within a lunar month. Spring tides (highest tidal range) and neap tides (lowest tidal range) occur twice each lunar month. Spring tides occur when the moon and sun are both on the same side of the Earth (new moon) or on opposite sides (full moon), so their tidal pulls are additive. Neap tides occur when moon and sun are 90° apart (first and third quarters). Tidal range also varies from month to month. Tides are composed of numerous components with different periods, each caused by a regular periodic change in the Earth–moon and Earth–sun orbits, such as distance or declination.

Tide Waves.

Tide waves appear to progress from east to west as the Earth spins under the tide bulges. Continents interrupt the tides everywhere except around Antarctica and cause tide waves to be dispersed, refracted, and reflected in complex ways that affect tidal characteristics differently at different locations. Because its wavelength is so long, a tide wave is a shallow-water wave that is refracted by seafloor **topography.** The tide wave is a forced wave because it is too slow, even in deep oceans, to match the orbital velocity of the Earth's surface as it spins, except near the poles. Tide waves are deflected by the Coriolis effect. In ocean basins of suitable dimensions, this deflection can create tuned-oscillation standing waves called amphidromic systems. The crest of one tidal component enters the basin and passes counterclockwise (Northern Hemisphere) or clockwise (Southern Hemisphere) around the basin to arrive back at the entrance exactly when another crest arrives

Tidal Currents.

Orbits within tide waves are so compressed, particularly in coastal and estuarine regions, that vertical tidal motion is very small in relation to the horizontal motions. The horizontal motions are tidal currents. Open-ocean tidal currents are weak, and their direction progresses in a rotary pattern during the tidal cycle. In coastal and estuarine areas, tidal currents generally reverse direction 180° as flood and ebb currents during the tidal cycle. Tides in such areas are usually combinations of progressive and standing waves, and the relationship between high or low tide and times at which slack water or maximum currents occur is different at each location. Tidal currents can be very strong, tidal range particularly high, and the progression of the tide wave complicated in estuaries where standing waves occur for some tidal components.

Tide Predictions.

Tides are too complex to be predicted without measurement at each location for which predictions are needed. Tidal-height measurements may now be made with satellite sensors. Tidal-height measurements recorded for several months or longer can be subjected to harmonic analysis. This analysis can allow the tidal range and times of high and low tides at the studied location to be predicted accurately. Tidal currents are more difficult to predict.

Energy from Tides.

Electricity is generated from tidal energy in a few locations where turbines and dams have been placed across a bay or estuary. However, very few locations have a sufficiently large tidal range to make such projects feasible. Suitable locations have unique ecology that depends on those tides.

KEY TERMS

You should be able to recognize and understand the meaning of all terms that are in boldface type in the text. All of those terms are defined in the Glossary. The following are some less familiar key scientific terms that are used in this chapter and that are essential to know and be able to use in classroom discussions or on exams.

amphidromic system
amplitude
antinode
centripetal force
Coriolis effect
crest
cum sole
current
declination
diurnal tide
ebb
estuary
flood
harmonic analysis
high-tide line
intertidal zone
low-tide line
lunar month
mixed tide
neap tide
node
orbital velocity
partial tide
pressure gradient
progressive wave
refracted
semidiurnal tide
shallow-water wave
slack water
spring tide
standing wave
tidal range
trough
tuned

STUDY QUESTIONS

1. If the mass of the moon were four times what it is, the distance between the Earth and the moon would be twice what it is now. Is this a correct statement? Explain why or why not.
2. Describe the imbalance between centripetal force and the gravitational attraction force at different locations on the Earth's surface. How is it created?
3. Where on the Earth's surface, in relation to the moon's direction, is the tide-generating force due to the moon equal to zero?
4. Why does the moon exert a greater tide-generating force than the sun, even though the sun's gravitational attraction at the Earth's surface is almost 200 times stronger than the moon's?
5. How are diurnal, semidiurnal, and mixed tides different? Why is it important to some sailors to know which type of tide is present in a port that they visit?
6. Spring tides and neap tides occur twice each month but are not the same height each month. What variations of the Earth's orbit around the sun might explain seasonal variations in the tidal range of spring or neap tides?
7. Why is the tide wave a forced wave in some places and not in others? Where is it a forced wave, and where is it not a forced wave? Why?
8. Why are amphidromic systems not established in all ocean basins? Why do some tidal components in a particular basin form amphidromic systems, whereas other components do not?
9. Why are tidal currents in the deep oceans slower than those in coastal waters? Why are deep-ocean tidal currents generally rotary, whereas coastal tidal currents are reversing?
10. How are tide tables able to predict the future times and heights of high and low tides? These predictions are generally accurate, but weather conditions can cause the heights and times of high and low tide to be shifted somewhat from those predicted. How can this happen? List and explain more than one possible reason.

CRITICAL THINKING QUESTIONS

1. What might happen if the mass of the moon doubled? How would the moon's orbit be affected? How would ocean tides on the Earth be affected?
2. Why is the tide wave a shallow-water wave? How would it be refracted as it approached a large island with a wide continental shelf?
3. Why is it necessary to build a dam across an estuary to get the greatest possible amount of energy from tidal power? Why couldn't we just put a number of turbines side by side across the entrance?
4. There is a proposal to build a sea-level canal with no locks to connect the Atlantic and Pacific Oceans across the Isthmus of Panama near the existing Panama Canal. Imagine that this canal was built instead across Mexico from the Gulf of Mexico and that it was several hundred meters wide and 30 m deep.
    - (a) Would it affect the nature of the tides in the Gulf of Mexico? If so, how?
    - (b) In the canal itself, would there be tidal-height variations of water level?
    - (c) Would there be tidal currents? If so, hypothesize what characteristics the tides and tidal currents would have.
5. Tidal bores are formed when a flood tide moves up an estuary or inlet faster than the speed that a shallow-water wave of tidal wavelength can sustain. When the tide ebbs in such inlets, is there a tidal bore that flows seaward? Explain why such an ebb tide bore does or does not exist.

CRITICAL CONCEPTS REMINDERS

CC12 The Coriolis Effect: Water masses move freely over the Earth's surface while the solid Earth itself is constrained to move with the Earth's rotation. This causes moving water masses, including long wavelength waves that comprise the global tide wave motion, to appear to follow curving paths across the Earth's surface. The apparent deflection is called the Coriolis effect. Coriolis deflection can create a rotary motion of the tide wave, called amphidromic systems, within certain ocean basins. Amphidromic systems rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

CREDITS

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