Marine Science Peter Castro | Michael E. Huber



(VII)

SECOND EDITION

Waves and Tides

4.1 Introduction to Wave Energy and Motion

- 4.2 Types of Waves
- 4.3 The Tides

Chapter

THEME Patterns

By making observations and collecting and analyzing data, scientists can find patterns that help them better understand the nature of waves and tides and predict their patterns.

BIG IDEA

Waves and tides are influenced by many factors and, in turn, affect marine organisms as well as humans.

About the photo A wave breaks as it approaches the shore off Cape Kiwanda, Oregon.

4.1 Introduction to Wave Energy and Motion

Main Idea

Waves carry energy across the sea surface but do not transport water.

Key Questions

- 1. What are the three most common generating forces of waves?
- **2.** What are the two restoring forces that cause the water surface to return to its undisturbed state?

Waves and tides are among the most visible of all ocean phenomena. Anyone who has swum in, sailed on, or simply walked beside the sea is familiar with waves and tides. Waves happen in every kind of body of water, whether you think of waves crashing on the shore, a surfer riding the perfect wave, the waves following a passing ship, or the ripples in a puddle when the wind picks up. In this chapter, we will describe the origin and parts of a wave and their characteristics, and we will describe the world's largest waves, the tides.

Wave Formation

Waves are started by disturbances called **generating forces**. Although there are many generating forces for waves, we will discuss the three most common ones—wind, earthquakes, and landslides.

How Waves Start When wind blows across the surface of a body of water, it creates friction between the air and the water. The drag along the water causes small **capillary waves** to form. Capillary waves are the smallest of the wind driven waves. They are also called ripples (Fig. 4.1). Patches of these waves are seen across the surface of the water on a windy day, and they disappear when the wind dies down. As the wind continues and capillary waves grow bigger, the surface of the water becomes rougher. When the smooth surface of the water is disturbed, more energy is transferred from the air to the water, making it easier for the wind to grip the water, forming even larger waves. If the wind continues to blow, it pushes the peaks of the waves up and stretches out the troughs. Larger waves are formed as the wind continues to increase, and they move away from their source slightly faster than the wind that formed them.

After the waves have moved away from the wind or storm that formed them, they settle into **swells**. Swells are evenly spaced waves with smoothly rounded crests and troughs. Swells start out as progressive wind waves, but as they organize into evenly spaced waves, the shorter waves from the storm dissipate, so only long waves carrying a large amount of energy are left. They are a subset of progressive wind waves even after they settle into swells. Swells carry energy very long distances across ocean basins. Groups of swell waves generated by

VOCABULARY

generating forces capillary waves swells tsunamis fetch restoring force crest trough amplitude wavelength period frequency wave cancellation

wave reinforcement



What is the biggest wave you've ever seen? A rogue wave is usually defined as a wave that is greater than twice the size of surrounding waves and can reach heights of up to 33 m. Rogue waves can cause severe damage to ships as well as injuring people aboard. One area of the ocean that is known for producing rogue waves is off the southeast coast of South Africa, where large swells meet the fast-moving coastal current.



Figure 4.1 Capillary waves, the smallest wind-driven waves, form on the surface of the water.



Figure 4.2 Swells are generated by the wind and can travel long distances across ocean basins.

large storms in the Pacific Ocean between 40° S and 50° S have been traced traveling north through the Pacific to the shores of Alaska. Swells closely follow the ideal pattern of waves, and when you think of gentle rolling waves in the open ocean, you are imagining swells. Swells are still categorized as progressive wind waves, but they are different from the progressive wind waves that are initially formed in storms; they are organized into a steady pattern of evenly spaced crests and troughs (Fig. 4.2). Storm-generated waves "relax" into swells as they move away from the storm.

A second generating force for waves is earthquakes. When the sea floor is disturbed, the water above it moves up or down with the sea floor. This causes a large amount of water to be displaced, and it can cause waves to move away from the source of the earthquake. These waves, called **tsunamis**, can travel very long distances and cause great damage to coastal areas. Tsunamis are not produced with every earthquake, and they can be very hard to predict.

The third most common wave-generating force is a disturbance created by landslides or ice breaking off glaciers. This process is similar to throwing a stone into a lake. When a large piece of land or ice enters the ocean, it moves the water out of the way. As the land or ice settles or sinks, the water that was displaced moves back to its original position. This movement creates a series of waves that move away from the location where the material originally entered the water.

Many factors influence the formation of waves. The first is wind speed. Higher wind speeds create larger waves. **Fetch**, or the distance of open water that the wind can blow across without changing distance, also influences wave formation. Areas that have a large fetch will produce more waves than areas with a small fetch; similarly, the wider the fetch, the more waves that can form (Fig. 4.3).

More waves are formed when wind continues for a long time. Water depth also influences wave formation. Waves are more easily produced in shallow areas than in deep water. Wave height is dependent on three factors: wind speed, fetch, and wind duration. The largest waves form when all three factors are maximized. Figure 4.4 shows the average wave height of the world's oceans. The most favorable conditions for wave formation occur between 40° S and 50° S, where there are large areas of open ocean with few landmasses to limit the fetch of the wind. Sailors call this area the "roaring forties" and "furious fifties" for the large and notorious storms that produce large waves. Predominantly westerly winds blow almost continuously in this area, which combined with a large fetch, produce very high waves. Large waves can be produced anywhere, but this area is infamous for the largest waves in the world.

Wave Dissipation The energy is dissipated, and the water particles stop moving because of restoring forces. A **restoring force** is a force that causes the water surface to go back to its undisturbed state. There are only two restoring forces—surface tension and gravity. Surface tension is responsible for restoring small capillary waves. Surface tension isn't strong enough to restore waves any bigger than small ripples of waves. Gravity is a powerful force that is responsible for restoring because and the strong large waves.

Wave Energy and Motion

A wave has two different types of energy—potential and kinetic. The potential energy comes from the height of a wave. Potential energy is the energy that an object has because of its position above the surface of Earth. The higher the wave is, the more potential energy the water within that wave has. The kinetic energy of a wave comes from the motion of the water particles. Kinetic energy is the energy of objects in motion, so the water particles in a wave exert kinetic energy when they move.

Orbital Motion Waves carry energy across the sea surface but they do not actually transport water. How can this be? It is important to remember that a



Figure 4.3 Wind speed is equal across this bay, but the fetch is longer on the wider portion, so the waves are bigger there.



Figure 4.4 Average wave heights across the globe. Areas in red have the highest average wave height, while areas in purple have the lowest.



Direction of propagation

wave is *energy* moving through the water, not just the physical movement of the water you actually see. Wave energy travels in a particular direction, the direction of propagation. As the wave energy moves through the water, it moves water particles up and down in an orbital motion. When a water particle moves with a wave, the wave energy causes the particle first to move up, then forward with the wave energy. The energy of the wave then continues forward, but the particle of water moves

down under its original position and back behind where it originally was. When the next wave arrives in that spot, the particle moves up and forward again, completing its orbit. Each particle of water in the wave only moves in circles, and only the energy of the wave continues to move forward (Fig. 4.5).

Wave Anatomy The highest point of a wave is called its **crest**, and the lowest point is its **trough**. Wave crests or troughs can be close together or far apart. The height of a wave is the distance from the crest to the trough, but scientists more often use the **amplitude** of a wave, which is one half of the wave height. The **wavelength** is the distance from crest to crest or trough to trough. The equilibrium surface is the undisturbed ocean surface, or sea level (Fig. 4.6).

Wave speed is determined by wavelength and wave **period**, which is the time it takes for two consecutive crests or troughs to pass the same point. The **frequency** is the reciprocal of the wave period. It is equal to the wavelength divided the wave period. In deep water, wave speed is dependent on the wavelength of the wave, not on the depth of the water. In shallow water, wave speed depends on water depth, not on the wavelength. After a wave is formed, its speed can change, but its period remains the same. The period of a wave is determined by the generating forces of the wave; so even as the wave moves, its period cannot change.

The surface of the ocean is much more complex than waves moving in a



of many different waves going in different directions because they were formed by winds of different speeds blowing in different directions for varying lengths of time. The intricate surface of the ocean results from the interactions of all the waves.

Figure 4.5 Water particles move in a circular pattern, the do not move in the direction of the wave. Anything floating on or in the water rear the surface moves in circles as well.

Figure 4.6 An idealized series of waves, with labeled anatomy.

Wave Interaction Wave cancellation occurs when the crest of one wave meets the trough of another, and the sea surface ends up being intermediate between the two, effectively canceling out the waves. If the crests of two waves collide, however, they add together to produce a higher wave which is called **wave** reinforcement (Fig. 4.7). Wave reinforcement can cause very large waves to form seemingly out of nowhere. These rogue waves can be as high as a 10 story building and can cause great damage. Oceanographers once dismissed rogue waves as rare or even nonexistent and nothing more than a sailors' myth, but they have now confirmed that rogue waves do occur. They might account for a significant fraction of the 100 or so large ships that are lost, or disappear, at sea each year (Fig. 4.8).

Wave reinforcement (waves in phase)



Wave cancellation (waves out of phase)





Figure 4.7 Wave cancellation results when waves meet out of phase. When waves meet in phase, however, wave reinforcement occurs.

Figure 4.8 Rogue waves – large waves in the open ocean that seemingly come out of nowhere – can be caused by wave reinforcement.

Reviewing the Main Idea

- **1. Describe** how wind waves are generated.
- **2. Explain** What two types of energy does a wave have? How can a wave have two different types of energy?
- **3. Illustrate** Draw a wave and include the following labels: crest, *trough, wave height,* and *wavelength.*

4.2 Types of Waves

VOCABULARY

deep-water waves shallow-water waves intermediate waves progressive wind waves refracted longshore transport rip currents tsunamis internal waves standing waves node antinodes



How can we protect coastal communities from tsunamis? Tsunami warning systems monitor ocean basins for earthquakes and the tsunamis that can be generated as a result. The warning systems help people take measures to get out of harm's way before a tsunami reaches shore. Tsunami warning systems in the United States are similar to tornado warnings. A broadcast by the Emergency Alert System is broadcast on television and radio, and sirens may go off as well. Designated evacuation routes exist in many coastal communities.

Main Idea

There are several types of waves, each with its own characteristics and different ways of traveling through the ocean.

Key Questions

- **1.** List different types of waves.
- 2. What does it mean when a wave is refracted?

There are two broad categories of waves: **deep-water** and **shallow-water waves**. The two categories of waves have different characteristics and travel differently through the ocean. Whether a wave is a deep-water wave or a shallow-water wave depends on the depth of the water and the wavelength. A wave can transition from being a deep-water wave to a shallow-water wave and vice versa depending on the depth of the water. Waves that are in between a deep-water wave and a shallow-water wave are called **intermediate** waves, having characteristics of both types (Fig. 4.9).

Deep-Water Waves

A deep-water wave is a wave that travels in water that is deeper than one half of its wavelength. The speed of deep-water waves depends on the wavelength of the wave, not on the depth of the water. Like all ocean waves, deep-water waves do not move water; they carry and move energy from one place to another. There are two main types of deep-water waves. Most waves that you see in the ocean or in large lakes are deep-water waves known as **progressive wind waves**. These waves are generated by wind, restored by gravity, and progress in a particular direction. We have already discussed one special type of progressive wind wave—swell waves. Deep-water waves form when swell







waves originate and travel in water that is deeper than one half of their wavelength. As swell waves approach the shore, they transition from deep-water to shallow-water waves. Wind-generated waves can be deep or shallow, depending on the depth of the water where the wave travels and the wavelength of the wave.

Shallow-Water Waves

Shallow water waves travel in water that is less than 1/20th of their wavelength. Their speed depends on the depth of the water, not on the wavelength of the wave. As a deep-water wave approaches the coast, its bottom starts to "feel" the bottom of the ocean (Fig. 4.10). The interaction of the wave and the sea floor changes the pattern of the orbits made by the water particles in the wave from circles to flattened circles, or ellipses. The friction between the waves behind it catch up, they get closer together, giving them a shorter wavelength. The waves pile up, becoming higher and steeper. A wave breaks, or spills over, when the bottom of the wave is slowed down by the sea floor but the top of the wave does not slow down, creating what is known as surf (Fig. 4.11). The energy that was originally put into the wave by the wind is expended on the shoreline as the wave breaks. If you are on a beach on a day when the waves are large, then you can feel the energy of a wave as it crashes onto the beach. Large surf waves seem to shake the ground and are so loud that they can make conversation difficult.

Figure 4.11 Waves change shape as they move from the open ocean to the coast. As the water gets shallower, the orbital motion of water particles shifts to become more elliptical. The drag of the wave across the bottom is what causes waves to break and form surf.



Figure 4.10 As waves approach the shore, the bottom of the wave slows down before the top, causing the wave to break and create surf.

(t)Purestock/SuperStock, (b)Source: Bill Ober





Figure 4.12 Waves refracting as they approach a beach

Figure 4.13 Various structures are built on beaches to prevent erosion due to longshore transport.

STUDY STRATEGIES

Concept Mapping Create a concept map comparing and contrasting deep water and shallow water waves. Add notes to your concept map after classroom discussions of Section 4.2, Types of Waves. **Wave Refraction** Waves are **refracted**, or bent, as they move from deep water to shallow water. When waves approach the shore, they usually do so at an angle. When the bottom of the waves slow down as the water gets shallower, the part of the wave that remains in deeper water continues to move at the original speed. Because of this, the waves "bend" and the waves along the surf are parallel to the shore (Fig. 4.12). Waves can also bend and wrap around an island depending on the sea floor surrounding the island.

Longshore Transport As discussed above, waves usually don't travel perpendicularly towards the shore. As a wave moves towards the shore, the particles of water are transported toward the shore and down the beach in the



Figure 4.14 The formation of a rip current

direction of the waves. This is called **longshore transport**. Longshore transport is responsible for moving sand and sediments down a beach. When the wave feels the bottom, the energy in the wave picks up sand and sediment on the sea floor. The energy of the wave moves the sand with it, so the sand ends up moving down the beach (Fig. 4.13). This also causes water to build up along the beach. The areas where it can return to the ocean are sometimes narrow. This creates **rip currents**, or areas of rapid seaward-flowing water (Fig. 4.14). These can be dangerous to swimmers. Beaches that are prone to rip currents often have signs warning swimmers, and most water-safety courses teach ocean goers to swim parallel to the beach if they get caught in a rip current.

Tsunamis Sudden movements of Earth's crust, such as an earthquake or an underwater volcano eruption, can cause **tsunamis**. Tsunamis, or seismic sea waves, can travel very long distances and cause great damage to coastal areas. If a large portion of Earth's crust is moved because of seismic activity, then the water column above it might be displaced. Gravity causes the water to be pulled back toward its equilibrium state, which creates a wave with an extremely long wavelength (200 km long or more). Because of their extremely long wavelength, tsunamis are actually shallow-water waves. They can travel very long distances across entire ocean basins at over 600 km per hour while carrying great amounts of energy. Because they carry so much energy, they have the potential to cause great damage when they reach the shore (Fig. 4.15).

Tsunamis can be several meters high at their origin, but that height is distributed over the entire length of the wave. If you add the other swells and disturbances in the ocean on top of that, then a tsunami can be hard to track across open water, which is another reason they can be so dangerous. When tsunamis reach shallow water, they break just like any other shallow-water wave, but they can create very large surges of water that can flood the coast for up to 5 to 10 minutes before flowing back toward the sea. Because tsunamis are hard to follow across ocean basins and because not all earthquakes produce

Figure 4.15 Tsunamis carry a great deal of energy, and can cause significant damage when they hit coastal communities.



Waves That Kill

Surfers and beachgoers who have been hit by a wave know how forceful they can be. Most waves are pretty harmless, but coastal storm waves cause damage every year, and sometimes deaths. Occasionally, seismic sea waves, known as tsunamis, unleash all of the awesome power.

Also called tidal waves, tsunamis are unrelated to tides and are produced by disturbances like earthquakes, landslides, and volcanoes. Tsunamis are much longer and faster than ordinary waves. They can have wavelengths of 240 km and travel at speeds greater than 700 km/h. In the open ocean, tsunamis are typically less than 1 m high and are hardly noticeable. They grow as they reach shore, but most tsunamis do little damage.

Fatal tsunamis Once in a while, though, tsunamis are devastating. In 1883 the volcano Krakatoa exploded, unleashing tsunami waves around half the globe that killed over 35,000 people. Fatal tsunamis occur every year or two on average, mostly in the Pacific because of the seismic activity around the Pacific Rim.. Between 1992 and 2011, tsunamis killed more than a quarter of a million people.

The deadliest tsunami struck the Indian Ocean on December 26, 2004, triggered by a massive earthquake off the Indonesian island of Sumatra. Within minutes of the earthquake, waves at least 10 m high (estimates are as high as 30 m) smashed onto Aceh, on the Sumatran coast. In less than eight hours tsunami waves radiated around the Indian Ocean, killing an estimated 230,000 people in 12 countries. Survivors suffered the loss of their homes, businesses, farms, schools and water and electricity supplies.

In the two years following the Indian Ocean tsunami, fatal tsunamis struck Haiti, Chile, Indonesia, and Japan. In Japan, in addition to killing nearly 16,000 people, the massive waves damaged a nuclear power plant in Kagoshima,, releasing radioactive material into the atmosphere and ocean. This made it the worst nuclear disaster since Chernobyl in 1986.

Surviving tsunamis To survive a tsunami, all you need to do is evacuate to higher ground, but in order to do this, you must know a tsunami is coming. A tsunami warning system was established in the Pacific for Hawai'i and the west coast of North America in the 1960s, and has probably saved



Worldwide death toll from tsunamis between the years 1992 and 2011.



Epicentel 20 Dec 04
Epicentel 28 Mai 0

Waves from the Indian Ocean tsunami of December, 26 2004 and the resultant toll of dead and missing. As with many other tsunamis, there was actually a series of waves rather than a single one. Most places were hit by three waves, with the second being the most destructive.

hundreds of lives. Another system was established in the Indian Ocean following the 2004 tsunami. Unfortunately, many coasts are not covered by warning systems, and even where they exist word may not get out to rural areas or people who aren't tuned in to the media. In Hawai'i, media and other electronic systems are supplemented by oldfashioned sirens, but this is the exception, not the rule. An even greater problem is that there may not be sufficient time to issue warnings. Fortunately, educating the public about the



The March 11, 2011 tsunami in Sendai, Japan washed away buildings and complete sections of the city in its path

relationship between earthquakes and tsunamis can be far more effective than tsunami warning systems. People on the coast need to understand that an earthquake might bring a tsunami. Many in earthquake-prone Japan knew to evacuate after the Sendai earthquake, reducing the number of casualties from that tsunami. In both the 2004 Indian Ocean tsunami and the one in Chile in 2010, schoolgirls were credited with saving hundreds of lives by raising the alarm. But in many places tsunami education still lags. The ocean breifly recedes as a tsunami approaches, and people sometimes move into harm's way to look at the exposed marine life. Where small earthquakes are common, people can become complacent. Even if they know to move to higher ground they may not respond appropriately.

Coastal resiliency Despite all of our scientific advances, we can't stop tsunamis. We can, however, make wiser choices regarding coastal development and engineering. Since the 2011 tsunami in Japan, higher seawalls are being built around many nuclear plants. Resiliency improves by protecting natural habitats such as reefs, mangrove forests, and salt marshes. As tsunamis move over these natural barriers, their energy is diminished through friction, mitigating the tsunami wave intensity that ultimately makes landfall. Humans living along coasts will always have to live with the threat of tsunamis, but with advanced warning systems, strong educational awareness programs, and natural habitat protection, we can adapt to minimize the damage.

Think Critically

- 1. What causes tsunamis?
- **2.** If a warning tells you a tsunami is headed your way, what should you do to increase your chances of survival?
- 3. What are some ways to protect against tsunamis?

GO ONLINE

To learn more about tsunami warning technology, access the inquiry activity available online.





Figure 4.16 Waters of different densities form internal waves below the sea surface (a). Internal waves are sometimes visible from the sea surface. In the Strait of Gibraltar, stratified water flowing between the saltier Mediterranean Sea (bottom right) and the relatively fresher North Atlantic Ocean(upper left) forms a large internal wave 100 m below the surface. The swell-like oscillations are visible from space (b).

tsunamis, oceanographers and geologists do not have a completely accurate tsunami warning system. Computer models help predict when a tsunami will arrive in an area, and pressure sensors across the ocean can help track a tsunami across the water. But even with these modern technologies, tsunamis can cause great damage to coastal areas.

Other Types of Waves

Waves traveling in depth between half and 1/20th of their wavelength are intermediate waves and have characteristics of deep- and shallow-water waves. If the wave is closer in depth to half of its wavelength, then it acts more like a deep-water wave. If it is closer in depth to 1/20th of its wavelength, then it acts more like a shallow- water wave. Intermediate waves show characteristics between deep and shallow-water waves.

Not all waves form at the boundary between air and water. Waves can form at any boundary between water of two different densities. Waves forming under the surface are called *internal waves*. Internal waves regularly form where water is stratified in layers of different densities (pycnoclines)(Fig. 4.16a). Where the waters meet, they oscillate and form a wave below the sea surface (Fig. 4.16b). Internal waves vary greatly in wavelength, and can have periods from seconds to hours. Internal waves are important in ocean mixing, especially in areas that have a large amount of freshwater runoff. Internal waves that form between the less dense fresh water and the more dense seawater help mix the two together. Internal waves can also play an important part in transporting eggs of fishes and other animals that reproduce in the open ocean to the coastal areas where the young fish grow into adults.

Deep-water, shallow-water, and internal waves are progressive waves, or waves that progress in a particular direction. Standing waves, in contrast, are waves that do not progress because they form in enclosed bodies of water such as bays and estuaries. Instead, they reflect back upon themselves. Imagine you have a rectangular basin with a flat bottom and sides. If you were to partially fill the basin with water and lift one side up, then rapidly set it back down, you would see that the water would flow back and forth within the container. If you did this repeatedly, you would see one area where the water stayed roughly the same height, with water oscillating up and down on either side. The point around which a standing wave oscillates is called the **node**. The high and low points at each end of a standing wave are called the antinodes (Fig. 4.17a). Standing waves form in enclosed coastal basins for the same reason they would form in your imaginary rectangular basin - instead of progressing forward, the wave hits a barrier (the geology of the basin) and reflects the energy back, forming a stable node around which the antinodes oscillate. The node of the standing wave is sometimes at the opening to the bay, so there is minimal water movement at the opening and larger movement at the end on the shore where the antinode is located (Fig. 4.17b)

Reviewing the Main Idea

- **1. Contrast** a deep-water and a shallow-water wave.
- **2.** Explain how a tsunami forms.
- **3. Describe** What are internal waves and where do they form?





Figure 4.17 Instead of progressing in one direction, standing waves oscillate around a single point called a node (a). Standing waves that form regularly in bays and inlets are popular tourist attractions and surfing spots (b).

4.3 The Tides

VOCABULARY

spring tides neap tides semidiurnal mixed semidiurnal diurnal flood tide ebb tide

tidal bores



When do we observe the highest high tides? They occur when the moon is either new or full and closest to Earth during its revolution. Every 28 days, during its elliptical orbit around Earth, the Moon reaches its nearest proximity to Earth. This is referred to as a perigee. Three to four times a year a new moon or a full moon will occur when the moon is in perigee. This produces perigean spring tides, a time when the highest high tides occur. In some low-lying coastal areas, perigean spring tides can cause minor flooding.

Main Idea

Tides result from the gravitational pull of the moon and the sun and from the rotation of the Earth, moon, and sun.

Key Questions

- **1.** What are tides?
- 2. What are the three main tidal patterns?

The sea surface has been rising and falling in the rhythmic pattern known as tides since the ocean formed. The tides are a dominant influence on nearshore sea life. They alternately expose and submerge organisms on the shore, drive the circulation of bays and estuaries, trigger spawning, and influence the lives of marine organisms in countless other ways (Fig. 4.18).

Tides do not affect the middle of the ocean basins. They have a pronounced effect on nearshore areas. In fact, there is an entire ecosystem called the intertidal zone that is determined by the tides and would not exist if it weren't for the rising and falling of the tides each day (Fig. 4.19).



Figure 4.18 Spawning in these grunion (*Leuresthes tenuis*) is precisely timed to coincide with the highest tides, when grunion can reach the uppermost parts of the beach. Similarly, the hatching of the eggs also corresponds to high tide so that the young can swim away.



Figure 4.19 The rise and fall of the tides forms the ecosystem known as the intertidal zone, which has unique inhabitants and characteristics.

What Causes Tides?

Tides are essentially very large waves that travel around Earth. The tides are caused by the gravitational pull of the Moon and the Sun and by the rotation of Earth, the Moon, and the Sun. The Moon and Earth are held together by gravitational attraction. The Moon's gravity is strongest on the side of the planet that is closest to the Moon. The Moon's gravity pulls the water in the ocean toward the Moon, so if Earth were covered Moon's rotail entirely by water, then the ocean would bulge toward the Moon (Fig. 4.20). On the opposite side of Earth, the Moon's gravitational pull is weaker, so the water does not move toward the Moon. In fact, it bulges away from the Moon because of centrifugal force, the same force that keeps water in a bucket if you swing it around very fast (see Fig. 4.20). Because of gravity, you would expect the water to flow from the bucket to the ground, but centrifugal force pushes the water back into the bucket and keeps it from spilling. This centrifugal force on Earth arises because, strictly speaking, the Moon does not revolve around Earth. Instead, Earth and the Moon rotate together around their combined center of mass, which lies at a point inside Earth that is offset slightly from the actual center of the Earth (due to the mass of the Moon). This is called the Earth-Moon system. The offset causes the Earth-Moon system to wobble slightly, like an unbalanced tire, and it creates a centrifugal force that pushes water away from the Moon. Thus, on a water-covered Earth, the ocean would form bulges on opposite sides of the planet, one bulge toward the Moon where the Moon's gravity dominates and the other bulge away from the Moon where centrifugal force predominates. The water would be deep under the bulges and shallow away from the bulges because the pull of gravity is stronger than the centrifugal force (see Fig. 4.20).



Figure 4.20 The Earth-Moon system. The Moon's gravity causes water to bulge toward it on the side of Earth closest to the Moon. On the opposite side, farthest from the Moon, centrifugal force causes water to bulge in the opposite direction.



Figure 4.21 Because the Moon moves while Earth is rotating, a full tidal cycle takes longer than one 24 hour day.

STUDY STRATEGIES

Question Session Study the spring and neap tides illustrated in Figure 4.22 with a partner. Question each other about the topic to deepen your knowledge. In addition to the rotation of Earth and Moon, Earth spins like a top on its own axis. As it does this, any given point on the planet's surface will alternatively lie under a bulge and under a shallow spot. High tide occurs when the point is under a bulge. Because Earth takes 24 hours to complete a rotation, the point will have two high tides and two low tides every day. The Moon actually advances a little in its own orbit in the course of 24 hours. It takes the point on Earth an extra 50 minutes to catch up and align directly with the Moon again. A full tidal cycle, therefore, takes 24 hours and 50 minutes, causing the high and low tides in an area to vary daily (Fig 4.21).

The Sun produces tidal bulges in the same way as the Moon. The Sun is much larger than the Moon, but it is 400 times farther away, so the effect of the Sun on the tides is only about half as strong as the Moon's. When the Sun and the Moon are in line with each other, which happens at the full and new moons, their effects add together. At these times, the tidal range, or the difference in water level between successive high and low tides, is large. Such tides are called **spring** tides because they seem to surge up like a spring of water. The name is unrelated to the season. When the Sun and the Moon are at right angles, their effects partially cancel each other. During these **neap tides**, the tidal range is small. Neap tides occur when the Moon is in the first and third quarters. Because the Moon is the dominant cause of the tides, a full tidal cycle is the same as a lunar cycle, which is 291/2 days. When the Moon is in the first quarter, the Sun and the Moon are at right angles to each other, which causes a neap tide. One week later during the second quarter, the Moon is full and the Sun, the Moon, and Earth are in alignment, so the combined gravitational pull of the Sun and the Moon will cause larger spring tides. The third quarter occurs one week later when the Sun and the Moon are back at right angles to each other and neap tides occur. In the fourth quarter during the new moon, another spring tide is produced (Fig. 4.22). The other planets in the solar system also have a minor influence on the tides according to their mass and distance from Earth.

Tide levels also change with the seasons because the distance between Earth and the Sun changes with the seasons. During winter in the northern hemisphere, Earth is closer to the Sun than it is during the summer, so the Sun has a stronger influence on tides. No matter what the season, the Moon always has the strongest influence on the tides.



Figure 4.22 Spring and neap tides result from the interaction between the gravitational pulls of the Moon and the Sun.

Tidal Patterns

Because of the continents and the shape of the sea floor, tides in the real world behave differently than they would on a water-covered Earth. There are three main tidal patterns: **semidiurnal**, **mixed semidiurnal**, and **diurnal**(Fig. 4.23).

Most places have semidiurnal tides as expected, meaning that they have two high and two low tides of approximately the same height each day. The east coast of North America and most of Europe and Africa have semidiurnal tides. Mixed semidiurnal tides occur when an area has two high tides and two low tides of different heights each day. Most of the west coast of the United States and Canada have mixed semidiurnal tides. Diurnal tides occur when there is only one high and one low tide each day. Diurnal tides are uncommon. They occur on the cost of Antarctica and in parts of the Gulf of Mexico, Caribbean, and the Pacific. The distinctions between the types of tides are not absolute; in most places, the tidal pattern varies shift between the different types. Southern



Figure 4.23 Tidal patterns can be semidiurnal (a), mixed semidiurnal (b), or diurnal (c). In many places the tidal pattern fluctuates.

California, for example, has a predominantly mixed semidiurnal tide, but on some days the tides are almost diurnal (Fig. 4.24).

Tides vary from place to place and time to time because of the effects of land and the sea floor. On a water-covered Earth with a perfectly flat sea floor, the tides would move in one smooth, symmetrical wave. In reality, however, the continents prevent that single wave from sweeping around the globe, essentially breaking it into several separate waves within individual ocean basins. Islands, ridges, basins, canyons, reefs, and other features further affect the waves. The tide at a given place thus depends on its location relative to these features. The tides are also influenced by variation in the orbits of the Sun and the Moon relative to the Equator, and the planets have small effects. Even weather affects the tides. Strong winds, for example, can pile water upon the shore, causing higher tides than would otherwise occur. In addition to these factors, tides are affected by ocean currents and the Coriolis effect. To predict the tides at a given place, oceanographers must combine observations of actual tides at that place with theoretical equations. They are then able to produce remarkably accurate tide tables that predict the time and height of high and low tides. Tide tables are available for most coastal areas.

Tide Levels The highest level that a tide rises in a day is called high water. Consequently, the lowest point that a tide drops is called low water. In a mixed semidiurnal tide, it is necessary to distinguish between the two high and two low tides; that is, between the higher and lower high water and the higher and lower low water. The tidal range is the difference between the highest high tide and the lowest low tide. The tidal range is not a constant number because it changes depending the high and low tides of the day.



Figure 4.24 The worldwide distribution of semidiurnal, mixed semidiurnal, and diurnal tides.



Average tides are calculated for a given place using many years of data. This helps oceanographers calculate tide levels. Average low tide is especially important in coastal navigation, where oceanographers use the average low tide to determine the actual depth of the water and when it is safe for boats to navigate through shallow water. Tide levels are given in distance from the mean sea level, which is why it is possible to have a minus tide. A minus tide occurs when a low tide is lower than the average low water level (Fig. 4.25).

If you are at the beach during a rising tide, called a **flood tide**, then you might notice that the beach is shrinking because the water is moving toward the shore. Similarly, if you notice that the beach growing, then you are probably at the beach during the **ebb tide**, when the water is rushing back toward the sea. The period of time between the flood and ebb tides is called slack water, when the water is still and not moving toward or away from the shore. Fishermen pay special attention to the flood and ebb tides because some fish travel with the tides. The waves in an area can change with the tides as well, so surfers are also known to watch the tides. The tidal currents during the flood and ebb tides can move very fast and, therefore, can be very dangerous.

Tidal Range The largest tidal ranges, the difference in water level between successive high and low tides, are seen in narrow basins. Tides in these long, narrow bays and estuaries produce a standing wave, or a wave that doesn't move forward and instead reflects on itself, oscillating within an enclosed basin. When the node of the standing wave is at the mouth of the bay and the antinode is at the shore, the tidal level is amplified because the standing wave oscillates around the node; so the wave is highest at the antinode or the shore. Inside the bay, the tide level is higher because the water level is affected by the standing wave and by the tide; outside the bay, the tide would be lower because it is only affected by the tide and not the standing wave. For example, the Bay of Fundy in Canada has one of the largest tidal range is only about 2 m, but at the shore the tidal range is as high as almost 11 m (Fig. 4.26). Accordingly, short,

Figure 4.25 A generalized tidal cycle





(b)

Figure 4.26 The Bay of Fundy, in Canada, has one of the most extreme tidal ranges in the world. The difference between low tide (a) and high tide (b) is almost 11 m.

wide bays or estuaries can reduce the tidal range because no standing waves form; near the edges of the bay, the tide will be apparent, but as you move along the shore (closer to the middle of the bay) the tide will not be as high as it is at the edges. Estuaries that have a large freshwater input might have decreased tides because of the difference in density between the incoming tide and the freshwater inputs. The saltier water coming in with the tide is denser than the input of fresh water from rivers, so the denser water travels along the bottom and is hidden by the freshwater—the tidal range might not be visible on the shore.

Tidal Bores Tides can produce waves that can travel very long distances. These **tidal bores** can be up to 8 m high and can travel as fast as 64 km/h. This makes them potentially dangerous phenomena that can cause great damage. Tidal bores affect shipping routes through estuaries and near river mouths. They are relatively rare and don't occur in every river and estuary. Tidal bores most commonly occur in shallow estuaries and river mouths that have very large tidal amplitudes. When the flood tide approaches the estuary and shallow water, it feels the bottom and starts to slow down, but because of the large



amount of water and force behind it, when the tidal bore breaks, it continues to move toward the shore and up the river. Bores can be dangerous because of their force and speed. An open area of beach can be covered by a tidal bore in minutes. The world's largest tidal bore occurs in the Qiantang River in China. The dramatic tidal range of the Bay of Fundy also creates a tidal bore in the upper potion of the bay (Fig. 4.27)

Figure 4.27 A warning sign posted at a beach in the Bay of Fundy, warning visitors about the dangerous tidal bore.

Between the Tides

The intertidal zone is the area that is below water at high tide and above water at low tide. It is often called the littoral zone and can contain many different types of habitats. One of those habitats is the tide pool, which form when the tide recedes and water is left in depressions in the rocks. They vary in size, depending on the substrate and the type of tides in the area.

Life in the intertidal Organisms that live in tide pools lead a challenging life. Tide pools go through many different extreme conditions over the course of one day. Temperature and salinity can vary, and organisms can be alternately pounded by rough waves or completely dry. During low tide, tide pools can become isolated from the surrounding ocean. Sun exposure may drive up the temperature of the water, and evaporation leaves the pool much saltier than the ocean. Alternately, rain can introduce fresh water, lowering the salinity in the pools. During neap tides or when there is little wave action, tide pools may dry up completely. During high tides, or when wave action is particularly strong, fresh sea water is introduced to the pools, This water brings much needed nutrients and balances the temperature and salinity. Sometimes, though, the waves are strong enough to wash tide pool residents away, so organisms must have a way to stay in place during times of strong wave action. Tide pool living isn't just about tolerating unfavorable conditions. Organisms adapted to such a volatile environment can survive quite well. Seaweeds grow easily because of high light levels and a regular supply of nutrients. Many animals, like snails and sea urchins, feed on this abundant food source. Tide pools often form in rocks, so there are many nooks and crannies in which animals can avoid predators. Some species of fish even use tide pools as nurseries.

Zonation Life in the intertidal zone is a competition for light, space, and food. Many organisms are adapted to live in one of four zones: the splash zone, or the high, middle, or low intertidal zone. The splash zone is highest up on the shore, and receives the least input from the sea. It may only be submerged during spring tides. Lichens and snails are common here. The high intertidal zone, below the splash

zone, is exposed to the air most of the time but is submerged during very high tides. Barnacles are often found in this zone. The middle intertidal zone is usually submerged, except for extreme low tides. Organisms common to the middle intertidal zone include sea urchins and sea stars. The low intertidal zone is submerged most of the time. It has the greatest number of organisms and an abundance of seaweeds.

Marine scientists know a lot about the intertidal zone because it is easily accessible. Many seminal experiments in marine ecology have been conducted in this ecosystem. The habitats and organisms of the intertidal zone will be further explored in Chapter 13.

Think Critically

- **1.** What causes the extreme differences in salinity in the intertidal zone?
- 2. What are some benefits to living in the intertidal zone?
- 3. What are the four zones of the intertidal environment?

GO ONLINE

To learn more about the physical features that shape the intertidal zone, access the inquiry activity available online.



Organisms in the intertidal occur as specific zones based on their ability to withstand desiccation and wave action. Here, different types of seaweed form bands.

Tide Measurements and Tables

Because so many factors determine when tides occur, we cannot simply predict the tides by looking at the Moon's location in the sky. Tide charts can be slightly off for a particular area because of the shape of the coast and the offshore ocean basin, or because strong winds force water higher up the shore. Coastlines are very diverse, so the tide table for a beach that is just a few miles away might be slightly different than the observed tides. Historical tide data together with theoretical tidal equations allow oceanographers to predict tide levels throughout the world.

There are 196 tidal stations in the United States, where tides are measured and kept in a large database. This sounds like a lot of stations, but the United States has an extremely long coastline and the stations are quite far apart. In between, local features can change the tides along the coast (Fig. 4.28). Underwater bathymetry, such as reefs and underwater canyons, and the shape of the coastline greatly affect how tides affect local areas.



Figure 4.28 Six of the 196 tidal stations on the coasts of the United States. These stations monitor actual tides along with other physical and chemical features of the seawater. You can see the variation in tidal patterns, which are based on the shape of the continental shelf and local shoreline.

Reviewing the Main Idea

- **1.** Explain What causes tides?
- 2. Compare and contrast spring tides and neap tides.
- **3. Illustrate** Draw a diagram of a mixed semidiurnal tide and label the high high water, low high water, high low water, and low low water points.



REVIEW QUESTIONS

Multiple Choice

- **1.** Which area of the ocean has the most favorable conditions for wave formation to occur?
 - **a.** between 0° and 10° N
 - **b.** between 0° and 10° S
 - **c.** between 40° and 50° N
 - **d.** between 40° and $50^\circ\,S$
- **2.** Which is responsible for moving sand down the beach?
 - a. circular orbit
 - b. elliptical orbit
 - **c.** longshore transport
 - d. rip currents
- **3.** A tide with one low and one high water per day is which type of tidal pattern?
 - a. diurnal
 - **b.** mixed diurnal
 - c. mixed semidiurnal
 - d. semidiurnal
- **4.** Internal waves are important for
 - a. longshore transport of sediment.
 - **b.** preventing ocean mixing in estuaries.
 - **c.** rip currents returning water to the ocean.
 - **d.** transporting eggs of animals that reproduce in the open ocean.
- **5.** What causes water on the side of the Earth opposite the moon to bulge?
 - a. refraction
 - **b.** seismic action
 - **c.** centrifugal force
 - d. gravitational force
- **6.** Where are the largest tidal ranges found?
 - a. narrow estuaries
 - **b.** large, broad bays
 - **c.** seas with high salinity
 - d. polar seas

- **7.** What factors and features can influence tides along coastlines?
 - a. location and sizes of underwater reefs
 - **b.** location and sizes of underwater canyons
 - **c.** shape of the coastline
 - **d.** all of the above

Short Answer

- **8.** Explain how wind speed, fetch, and wind duration influence the formation of waves.
- **9.** What is the role of centrifugal force in forming tides?
- **10.** Why do tides vary from place to place and time to time?
- You observe a beach ball out on the open ocean. Even though the waves appear to move toward you, the beach ball seems to stay out on the ocean, bobbing in place. Explain this phenomenon you are observing.
- **12.** Explain why tsunamis are classified as shallow-water waves.

Critical Thinking

- **13.** Most tsunamis occur in the Pacific Ocean. How would you explain this?
- 14. If you owned a seaside home and a bad storm brought heavy winds and high surf to your coast line, would you prefer it to be during a new moon or a quarter moon? Why?
- **15.** Scientific disciplines in reality are not separated neatly into categories as they are in school classrooms. This chapter connected waves and tides to biology, chemistry, physics, astronomy, and anthropology. Discuss patterns you see that are cross-cutting each of these disciplines, citing examples from the text.

DATA ANALYSIS LAB

Why does comparing real-time data against

computer models matter? On December 26, 2004 one of the most devastating tsunamis in history swept across the Indian Ocean basin. More than 200,000 people were killed and billions of dollars in damages were incurred. With this particular tsunami, scientists were able to collect the most real-time data than ever before, giving scientists new insight into the behavior of tsunamis.

Data and Observations

The graph shows the relative height of sea level in the Indian Ocean on December 26, 2004, about 2 hours after the earthquake that generated the tsunami occurred. The blue lines show sea height as recorded by the Jason-1 satellite, the green portions show sea height as predicted by a computer model at the time.



Claim, Evidence, Reasoning

- **1.** Claim How can the accuracy of computer models of tsunamis help both scientists and the public?
- **2.** Evidence How do the data predicted by the model compare to the real-time data from the satellite?
- **3. Reasoning** How might the continued comparison of real-time data to computer models help improve the accuracy of future models?

CHAPTER PROJECT

Chapter 4 Project: Coastal Resiliency Planning

In recent years, coastal town and cities have started bringing their attention to coastal resiliency planning. Preparing for 10-year, 50-year, and 100-year flood scenarios enables these coastal communities to be ready to anticipate, mitigate, and recover from the effects of extreme weather events and issues related to a changing climate. The RESTORE Act provides a unique motivation for communities located on the shores of the Gulf of Mexico to come together and discuss how to best prepare for natural disasters. Their discussions lead to project proposals, some of which could become eligible to receive RESTORE Act funds.

Many stakeholders are involved in RESTORE Act meetings, all along the Gulf coast. Government agencies, non-profit organizations, businesses, and local concerned citizens are all working together to develop ideas and propose projects for funding. What projects are currently being suggested? How will these projects benefit the community in question?

You will:

- research proposed projects that will help protect or restore coastal communities
- present your findings to the class and share your opinion on whether the proposed project should receive funding and why.

GO ONLINE

To begin your research, go online to access your chapter project.

*Data obtained from: Geist, E. L., V. V. Titov, and C. E. Synolakis, 2006. Tsunami: Wave of change. Scientific American, vol. 294, no. 1, January, pp. 56–63.