

CHAPTER 9

Waves

CRITICAL CONCEPTS USED IN THIS CHAPTER

CC5 Transfer and Storage of Heat by Water

CC9 The Global Greenhouse Effect

CC12 The Coriolis Effect

CC13 Geostrophic Flow



FIGURE 9-1. A large ferry boat rests inland amidst destroyed houses in Miyako, Iwate, Japan. The houses were destroyed and the ferryboat and other boats carried inland by a tsunami that followed a 9.0 magnitude earthquake on 11 March 2011. The earthquake and tsunami killed about 27,000 people, most of whom survived the earthquake only to be overcome by the tsunami.

We are very much aware of continuous wave motion anytime we sail or visit the **shore**. Even on the calmest day, the water still laps gently onto the **beach** or rocks. If we stay long enough, we also notice that in most places the water level rises and falls on the shore as the hours pass. This slow up-and-down oscillation of the ocean surface is the incoming and outgoing **tide**. Because the high point of the wave (high tide) is separated by hours from the low point of the wave (low tide), we do not think of tides as waves. However, tides, which are discussed in **Chapter 12**, are a form of wave motion.

For all who visit or live near the shore, ocean waves are important. Waves provide enjoyment for people who visit the shore, and, as described in **Chapter 11**, waves are responsible for building and maintaining the sand beaches that are essential to many of our recreational activities. Unfortunately, waves also drown the unwary, **erode** beaches and **coastlines**, and damage

piers and other structures. Waves and tides are also important because they affect the navigation and safety of the myriad commercial and recreational vessels that ply the world oceans. This chapter describes what ocean waves are, how they are formed, and how they behave. Knowledge of the behavior of waves can enhance our enjoyment of activities such as swimming, surfing, **scuba** diving, sailing, or just standing by the water's edge watching the **surf**. It can also protect us from the dangers that waves often present.

COMPLEXITY OF OCEAN WAVES

Ocean waves are complicated motions of the water surface. The surface of the water oscillates up and down, sometimes only a few centimeters and sometimes several meters, but the oscillations are never exactly regular. Successive waves are of different **wave heights**, and the **wave period** also varies. Sometimes there may seem to be a pattern, especially on days with little or

no wind. On such days the waves appear to be less complicated, and the intervals between successive waves are usually longer. However, on the open sea during a storm, waves appear to break at random times and places. In addition, waves that roll in toward shore do not all break at exactly the same distance from shore, and each breaking wave looks a little different from the preceding one.

Although they are complex, ocean waves are not difficult to understand. The reason for the complexity is that what we see at any one place and time is a combination of many different waves. The combination of two or more simple waves of different periods or of two waves traveling in different directions is called **wave interference**, and this process produces complex waveforms. We can see how waves interact and combine in a lake or even a bathtub. When we throw a stone into a lake, the waves (usually called “ripples” if they are small) radiate outward in neat, regular, circular patterns from the point of impact. When we throw two stones into a lake a few meters apart from each other, the waves radiate in regular, circular patterns from each point of impact. Where the waves from one stone meet the waves from the other stone, a complicated wave pattern develops on the water surface as the two sets of waves interact.

If we watch carefully, we may be able to see that the two sets of waves are not really altered when they meet. Each wave simply passes through the other set, maintaining its original form and direction. The complicated surface pattern arises where the two sets of waves cross each other because the vertical displacement of the surface is the sum of the displacements of each of the two sets of waves at that point in space and time. We will return to the concept of wave interference later. For now, the important point to understand is that even the most complicated seas are the sum of a number of different simple waves of different heights and periods that may come from different directions.

PROGRESSIVE WAVES

Waves that we create by throwing a rock into a lake and waves that we see on the ocean move freely on the water surface. Therefore, they are called **progressive waves** (Fig. 9-2). Another type of wave, called a **standing wave**, behaves differently, as discussed later in this chapter.

If we look carefully at the ripples caused by tossing a rock into a lake, we see that a series of waves, not just a single wave, moves out from the impact point. Each of the individual waves has a rounded top where the water surface is elevated (Fig. 9-2a). The point of highest elevation of the wave is the wave **crest**. Between each successive pair of crests is a rounded depression of the water surface, or **trough**. Most progressive waves, whether in a lake or in the deep ocean, also have this general shape.

Waves also have several other important characteristics (Fig. 9-2a). The distance between two adjacent crests (or troughs) is called the **wavelength**, represented as L . Wave height (H) is the vertical distance between crest and trough, and wave **amplitude** is equal to $H/2$, the vertical distance between the crest or trough and the mean water level. Wave period (T) is the time the wave takes to move a distance equal to one wavelength. It is equivalent to the time that elapses between the arrival of two successive crests (or troughs) at a point on the surface. Wave period is measured as the number of seconds per wave. Wave **frequency** (f) is the number of wave crests (or troughs) that pass a point on the ocean surface in a given time. It is measured as the number

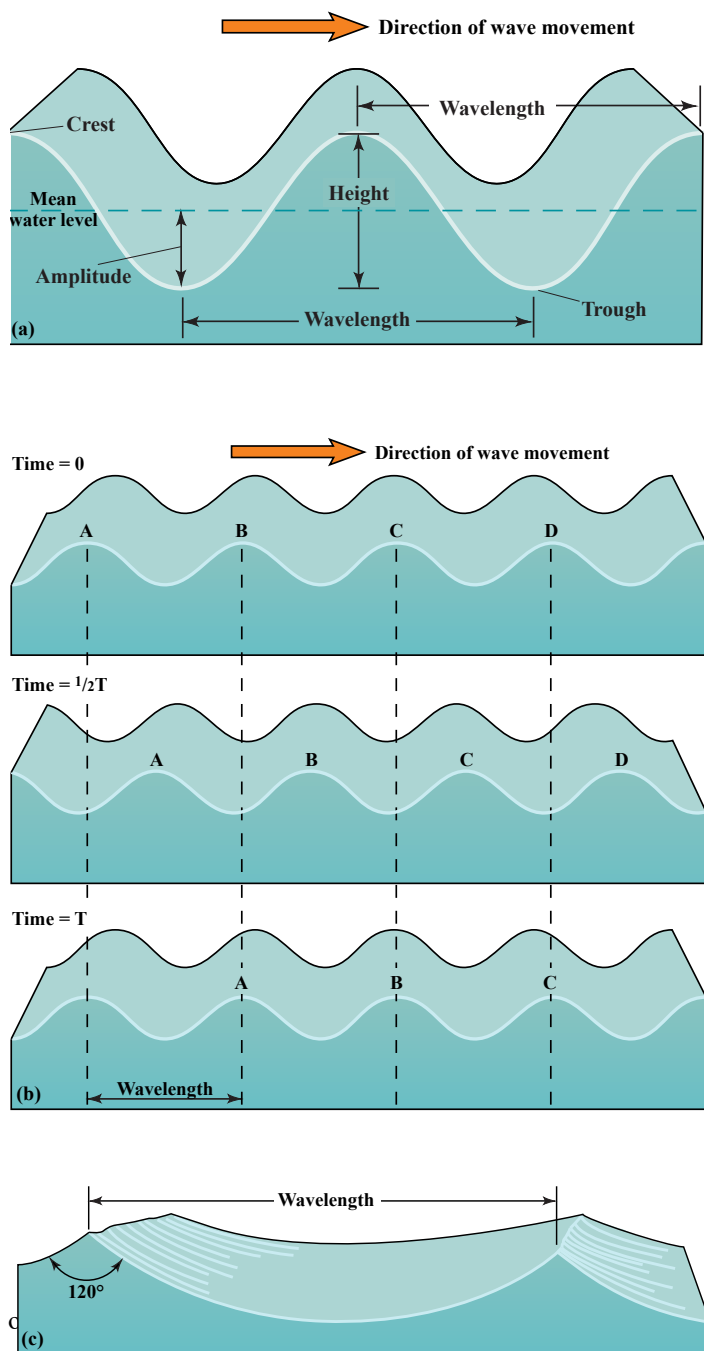


FIGURE 9-2. (a) All waves can be characterized by the presence of a crest and a trough, and by their wavelength (L) and wave height. (b) Progressive waves travel over the ocean surface at a speed that can be characterized by their period (T) or their frequency (f), which is the inverse of the period. Most progressive waves are smooth sine waves with rounded crests and troughs. (c) As waves are built by the wind, they develop a pointed crest and become trochoidal in shape.

usually measured in seconds, and wave frequency (f) are related by a simple equation:

$$T = 1/f$$

or

$$f = 1/T$$

We can estimate frequency without a stopwatch by counting the number of waves that pass in several minutes and dividing by the elapsed time (in seconds).

Two other important characteristics of progressive waves, **wave speed** and **wave steepness**, can be determined from the

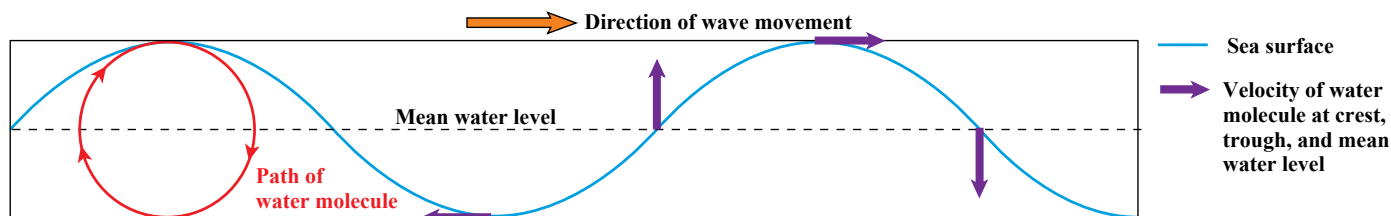


FIGURE 9-3. In a progressive wave, water at the crest is moving forward but has no vertical velocity. After the crest passes, the forward velocity slows, and vertical velocity increases until, halfway between crest and trough, the velocity is entirely vertical. As the wave continues forward, the vertical velocity is slowed, and the water gains velocity in the backward direction. At the trough, the vertical velocity is zero, and the backward velocity is at a maximum. The waveform moves forward, but each particle of water moves in a circular orbit whose diameter equals the wave height (for water at the surface) and returns to its starting point after each wave. You can see this for yourself if you push down on a water bed. The wave travels across the bed, but the plastic “surface layer” returns to its original location after the wave has passed.

wavelength, wave height, and period or frequency. Wave speed is often called “celerity” (abbreviated *C*) because there is essentially no net forward movement (or speed) of the water as the wave passes. As explained later in this chapter, only the wave energy and waveform, and not the water, move forward with the wave. Wave speed (*C*) is the ratio of the wavelength to the wave’s period and can be calculated using the following equations:

$$C = L/T$$

or

$$C = f \times L$$

Wave steepness is equal to the ratio of wave height to wavelength (H/L).

WHAT IS WAVE MOTION?

When a wave moves across the ocean surface without breaking, there is almost no net forward motion of the water itself. As we can easily see at the shore, objects such as logs and surfers floating outside the **surf zone** are not carried inshore with the waves. As waves pass, the floating objects ride up and down on each wave but remain at almost the same location indefinitely. Surfers must paddle forward to “catch” a wave before they can ride it inshore.

If water moved forward with the wave, the world would be an entirely different place. If you have walked or swum out through the surf on a beach, you have experienced what this would be like. When a wave breaks on the beach, the foaming water in the wave crest does move forward faster than the water under the wave is moving back away from shore. Walking or swimming through the surf is difficult because each wave tends to knock you down and carry you back toward the beach until the trough of the wave arrives and carries you seaward as water drains down the beach. However, once you have passed through the surf zone, the same waves that knocked you down in the surf no longer push you toward the beach. Imagine the difficulty ships would have if water on the open ocean were transported in the direction of the waves, in the manner that water in the surf zone is.

Wave Energy

A wave has both **kinetic energy** and **potential energy**. Kinetic energy is possessed by water molecules that are moving in the wave, and potential energy, by water molecules that have been displaced vertically against **gravity** and **surface tension**.

At the wavelengths of most ocean waves, the total energy (*E*) per unit area of a wave is approximately:

$$E = 0.125(\rho r H^2)$$

where ρ is the absolute **density** of water (in $\text{g}\cdot\text{cm}^{-3}$), g is the acceleration due to gravity ($9.8 \text{ m}\cdot\text{s}^{-2}$), and H is the wave height

(in m). E is measured in **joules** per square meter ($\text{J}\cdot\text{m}^{-2}$). Wave energy does increase with wavelength, but this factor is only important for waves of very long or very short wavelength.

Because water density changes very little in the open oceans (**Chap. 5**) and g is a constant, the total energy of a wave depends primarily on its height. The total energy of a wave is multiplied by a factor of 4 if the wave height is doubled.

Restoring Forces

Instead of moving forward with the wave, each water molecule within a wave moves in an orbital path. In deep water, the orbital path is circular (**Fig. 9-3**). Only the waveform and energy associated with the wave move forward. For the waveform to move forward, a restoring force must exist that tends to return the ocean surface to its original flat configuration after the water is initially displaced.

The principal restoring forces acting on ocean waves are surface tension and gravity. Surface tension pulls the surface equally in all directions, contracting the surface to its minimum area—a flat plane (**Chap. 5**). A trampoline provides a good analogy for surface tension. The trampoline surface is depressed and stretched when someone lands on it, but its “surface tension” causes it to snap back to its normal flat configuration, launching the trampoliner into the air.

Gravity acts on water molecules within a wave and causes a **pressure gradient** to develop beneath the sloping surface of the waveform (**Fig. 9-4**). The water flows in response to the pressure gradients and tends to flatten the ocean surface. In simpler terms, gravity causes the water to move downwards from the high parts of the wave to fill the depressions and restore the surface to a flat configuration.

Although interactions of restoring forces with water molecules in the wave are somewhat complicated, the principle is straightforward. Consider a water molecule located at the high point of an elevation of the ocean surface. The water molecule has potential energy because it is elevated above the mean water level. The restoring forces accelerate the molecule downward, and potential energy is converted to kinetic energy.

When the molecule reaches the mean surface level, its initial potential energy has been converted to kinetic energy and its motion is vertically downward. Because it has kinetic energy, it continues its downward motion but is slowed by the restoring forces. As it slows, kinetic energy is converted to potential energy. The molecule will continue in motion until all of its kinetic energy is converted to potential energy, at which point the molecule is at the same distance below the mean surface level as its starting point was above that level.

This process explains why water moves up and down as po-

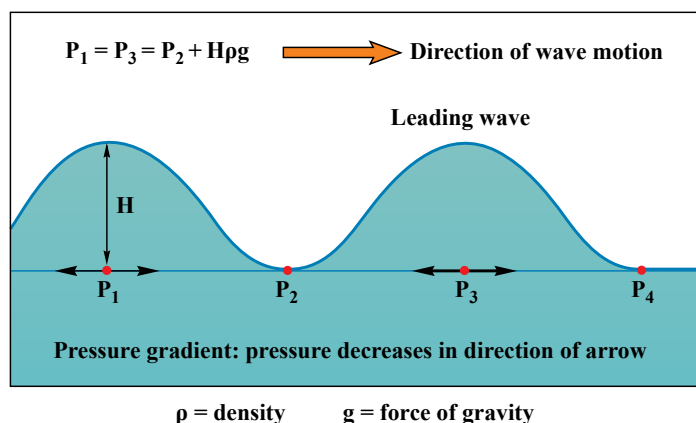


FIGURE 9-3 The horizontal pressure gradients under a wave illustrate how waves move. The pressure difference between locations directly beneath the crest and locations at the same depth beneath the trough tends to move water away from each crest toward the trough. Between two crests, the pressure gradients are symmetrical and tend to move water toward the trough. However, the water under each crest has kinetic energy because it is moving forward with the wave motion, and this energy is transferred forward from wave to wave with the wave motion. In front of the leading wave, the pressure gradient tends to move the water forward, displacing the still water surface in front, transferring some of the kinetic energy into potential energy, and beginning the wave motion. Some energy is transferred backwards from the last wave of a group of waves, in much the same way, to form a new wave at the back of the train.

tential energy is converted to kinetic energy and back. Why, then, do water molecules in a progressive wave move in a circular path and not simply oscillate vertically up and down, falling from crest to trough and then flowing back up to the crest to repeat the cycle? In fact, this simple vertical oscillation can occur at some locations where a vertical barrier exists at the exact location of a wave crest or trough. Where this happens, the wave is not a progressive wave but instead is a standing wave. Standing waves (discussed later in the chapter) behave differently from progressive waves.

In contrast, if no barrier is present, the leading wave of any series of waves is adjacent to an undisturbed water surface. The horizontal pressure gradient under the leading wave moves water molecules toward the undisturbed surface (**Fig. 9-4**). This movement causes the undisturbed water surface at the leading edge of the wave to be displaced. Thus, the restoring force (gravity) causes a disturbing force that transfers energy to undisturbed water ahead of the leading wave, wave energy is translated forward, and the wave is progressive.

The two restoring forces, gravity and surface tension, act on all waves. Gravity is the principal restoring force for most waves within the range of wavelengths normally present in the oceans, and such waves are often called **gravity waves**. In contrast, for waves with very short periods (<0.1 s) that can have only very small wave height (for reasons discussed later), gravity is less important and surface tension is the principal restoring force. These small waves are called **capillary waves** because capillarity is another term for surface tension. For waves with very long periods, such as the tides, an additional restoring force, the **Coriolis effect** (**CC12**), which is not actually a “force,” is important (**Fig. 9-5**).

MAKING WAVES

Once they are created, waves must have a restoring force to sustain the wave motion, but waves must be formed initially by a displacing force. Small waves can be created by small displacing forces acting over short periods of time. Large waves can be created only by large displacing forces or lesser displacing forces exerted continuously for extended periods of time.

Most ocean waves are caused by the interaction of winds with the water surface, but waves are also created by impacts on ocean water, by rapid displacement of ocean water, by gravitational attraction between the Earth, moon, and sun, and by the passage of vessels or marine animals through the ocean surface. The ocean waves created by these various processes vary from waves with a period of less than one-tenth of a second to waves with a period of more than a day (**Fig. 9-5**).

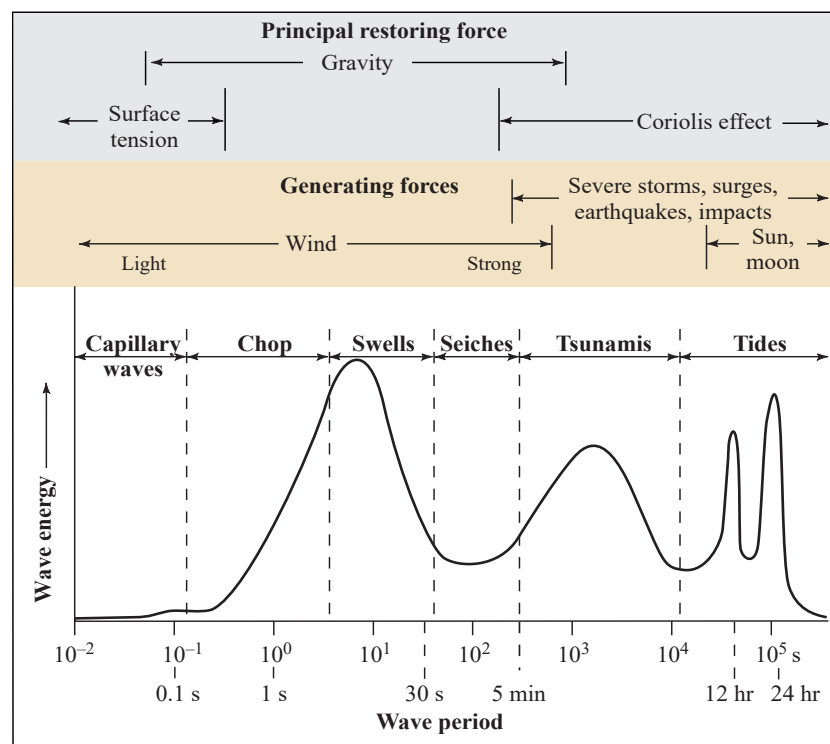


FIGURE 9-5. It is estimated that most of the energy associated with waves in the world’s oceans is contained in wind waves that have periods of between 0.2 and 30 s. However, there is also considerable energy associated with tides (periods of 12 h and above) and, despite their infrequent occurrence, considerable energy is also associated with tsunamis and severe storm waves (periods between about 1 min and 1 h). The smallest waves, capillary waves, are created by winds and restored principally by surface tension. Winds are responsible for creating most waves with periods less than about 15 min, and gravity is responsible for restoring all except the shortest-period capillary waves within this range of periods. Longer waves are formed by earthquakes and tidal forces, and the Coriolis effect is the principal restoring force for the longest waves.

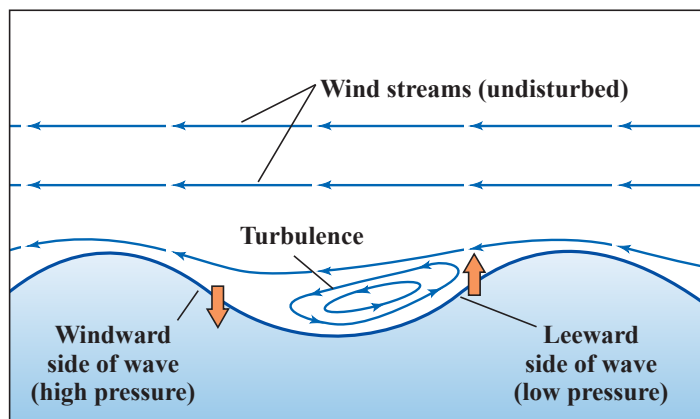


FIGURE 9-6. When the wind speed is great enough to form waves, the waves interfere with the wind flow immediately above the surface of the water. The wind pushes harder on the elevated, windward surface of the wave, and the air pressure is slightly lower on the leeward side of the wave than on the windward side. These forces combine to increase the height of the wave.

Impact and Displacement Waves

Waves can also be created by impact or displacement. For example waves can be created by earthquakes or volcanic explosions that cause the seafloor to move abruptly, and by meteorite impacts on the ocean surface. Rapid displacements of ocean water can be caused by seafloor **slumps** (landslides) and **turbidity currents**, and by collapses of coastal cliffs. Such impacts can create waves with very long periods (typically 10 to 30 min) called **tsunamis** (or sometimes “seismic sea waves”). Tsunamis are occasional events and contribute only a fraction of the total wave energy of the oceans (Fig. 9-5), but they can be extremely destructive.

Impact and displacement waves can also be generated by comparatively minor events, such as whales and dolphins jumping out of the water and ships moving through the water leaving wakes. Waves created by these minor impacts are insignificant in number and intensity, in comparison with wind-generated waves. However, in sheltered harbors ship wakes may be the principal source of wave energy and erosion of the **shoreline**.

The gravitational attraction between the Earth, moon, and sun is the force that creates waves that we know as tides (Chap. 10). Tide waves have periods of predominantly about 12 or 24 h and contribute a significant amount of the total wave energy of the oceans (Fig. 9-5).

Wind Waves

As we know from experience, winds are highly variable, or gusty, and may change speed and direction from second to second. Air moving over a land or ocean surface becomes **turbulent** when more than a gentle breeze blows. Small variations of wind speed and pressure that occur as the wind blows across a smooth ocean surface are believed to lead to the creation of capillary waves, which then grow larger if the wind continues to blow. Capillary waves have a maximum wavelength of 1.73 cm, rounded crests, and V-shaped troughs.

Winds generate waves on lakes and other fresh water bodies as well as in the oceans. While ocean waves are considered here, the principles of wind wave generation discussed in this section apply equally to all water bodies, including bodies such as lakes, estuaries, and rivers.

The mechanism by which wind generates capillary waves is not fully understood, but two factors seem to be important. First,

because of turbulence in the atmosphere, atmospheric pressure is slightly increased at some locations at the sea surface compared to locations a few millimeters or centimeters away. In these areas with slightly higher air pressure, the sea surface tends to be slightly depressed in relation to the adjacent ocean surface, where the pressure is lower. Thus, when winds blow across a perfectly flat sea surface, tiny areas of elevated or depressed sea surface are formed. Second, when winds blow over the ocean surface, a **shear stress (friction)** develops between the air and water because of the velocity difference across the air-sea interface.

The formation of capillary waves increases the roughness of the surface, which in turn increases the shear stress between wind and ocean surface and this enhances the ability of the wind to build larger waves. Capillary waves also alter the sea surface, so that some areas are tilted slightly up toward the wind (windward side) and others (**leeward** side) are tilted slightly away from the wind. The wind pushes harder on the back of the wave than on the front, further accelerating and building the wave (Fig. 9-6).

Wind-wave interaction actually is more complicated than this simple description suggests. For example, a wave generates turbulence as the wind flows across the water’s surface just as an aircraft wing alters the airflow to provide the lift necessary for a plane to fly. Once a wave is formed, the wind tends to build the wave height, primarily by uplifting the leeward side of the wave. In addition, differences in wave speeds cause small capillary waves to combine into the longer-period, higher waves called gravity waves. In this way, as the wind continues to blow across the sea surface, wind energy accumulates, and longer-period waves form. These longer period waves comprise most of the ocean’s wind wave energy (Fig. 9-5).

SEA DEVELOPMENT AND WAVE HEIGHT

As a wave’s height is built up by winds, its shape is modified from that of capillary waves. The shape first becomes close to the smooth sine wave form shown in Figure 9-2a,b. Subsequently, the crest and trough are modified progressively as the wave builds, and the wave shape becomes trochoidal (pointed crests and rounded troughs; Fig. 9-2c). As wind energy is absorbed by waves, their height, speed, period, and wavelength are increased.

Winds never blow uniformly over the water because they are highly variable in both time and space. Consequently, in the area where the waves are formed by the wind, waves of many different heights, wavelengths, and even directions of travel are present at the same time. Mariners refer to this confused state as a “**sea**.” In a “**calm**,” there are no significant waves, and the sea surface is flat. In a “**swell**,” waves are generally smooth, mostly of the same wavelength and from the same direction. How a sea becomes a swell is explained later in this chapter when we consider **wave dispersion**.

Waves sometimes break in deep water just as they do near the shore, but waves breaking in deep water are often called “**white-caps**.” Waves break because they have become too steep. When the steepness of a **deep-water wave** (H/L) reaches 1:7 (wave height equals one-seventh of wavelength), the wave becomes unstable and the crest tumbles down the forward slope of the wave, creating a breaking wave. If winds are very strong, the tops of the largest waves may be blown off by the wind.

Waves break when they have reached their maximum possible height for the wind speed. They also break when seas are developing and the waves cannot be modified quickly enough to longer

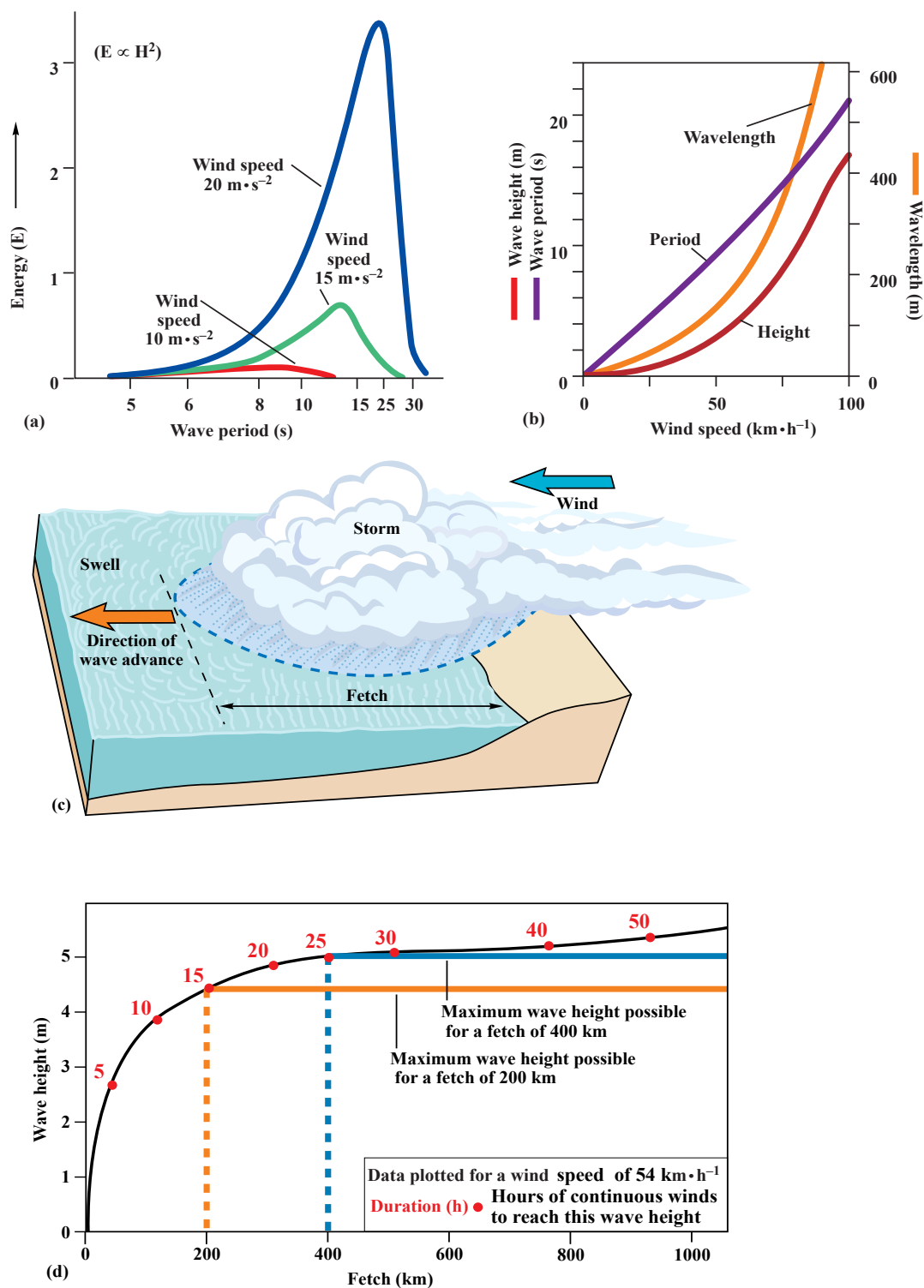


FIGURE 9-7. Relationships between wind speed, fetch, the length of time over which the wind blows, and the characteristics of the waves that are formed. (a) Strong (higher-speed) winds produce storms with greater total wave energy, and this energy is stored in waves of longer periods. (b) Strong winds also produce waves that have longer wavelengths and greater wave heights, provided that the winds blow long enough and have sufficient fetch. (c) The fetch is the distance over which the winds blow across the water to create waves. Fetch can be limited by the presence of a coastline or, where the storm is completely over water, by the dimensions of the storm itself. (d) The maximum wave height that can be reached is limited by the fetch, and this maximum wave height is reached only if the winds blow for a sufficiently long time.

wavelengths and greater heights to absorb the energy introduced by the winds. As a wave becomes oversteepened and breaks, some of its energy is dissipated by turbulence, which releases heat. Consequently, this excess energy cannot be used to increase the wave height.

Factors Affecting Maximum Wave Heights

A sea is said to be fully developed when the amount of wave energy lost to turbulence in breaking waves is equal to the difference between the total energy input from winds and the amount of wind energy needed to maintain the sea. Waves of many different heights and periods are present in a fully developed sea, but

storms with stronger winds produce waves with longer maximum periods than are produced by lower wind speeds (Fig. 9-7a,b). The maximum height of waves created by any specific storm or series of storms depends on the wind speed and the length of time the wind blows. The maximum height also depends on the wind **fetch**, which is the uninterrupted distance over which the wind blows (Fig. 9-7c). In shallow water (depth less than one-half of the wavelength), water depth is a limiting factor.

Figure 9-7d shows the effect of wind duration and fetch on maximum wave height. As the wind begins to blow, waves accumulate energy from the wind. Wave height initially increases rapidly, then at a progressively slower rate. However, if the fetch

is small, the maximum wave height is limited because waves relatively quickly travel out of the area where the wind is blowing. We can see the effects of a small fetch in lakes or in harbors protected from ocean waves. The fetch is restricted in such areas because the waves encounter a shoreline. No matter how strong winds are or how long they blow, only small waves can be created in harbors and all but the largest lakes.

The highest ocean waves are created where winds are strong and blow persistently over long fetches. High waves can also be generated when a series of strong storms passes in the same direction across the same fetch over a period of several days or longer. In this situation, some of the shorter-wavelength waves created by one storm do not have time to travel out of the area before the next storm arrives. Each successive storm simply builds on the height of waves remaining from preceding storms.

Maximum Observed Wave Heights

Persistent winds and storm tracks are arranged in bands with an east-west orientation (**Chap. 7**). Therefore, calm regions alternate with stormy regions from north to south in the oceans. The calm regions limit the fetch that can occur in a north or south direction in the ocean basins, but that does not mean that waves travel only east or west. First, the **trade winds** and **westerly** winds in the east-west wind bands do not blow directly east or west. Second, storms produce rotating winds and, thus, winds and waves of all directions. Third, if waves encounter a landmass or **reef**, the direction of wave travel may be altered as discussed later in this chapter.

Not surprisingly, high waves are most common in the Pacific Ocean because the Atlantic and Indian Oceans are much narrower and provide a more limited fetch. The longest fetches are within a band of westerly winds stretching around Antarctica.

A giant wave at least 34 m high was measured by the U.S. Navy vessel *Ramapo* on 7 February 1933 in the tropical North Pacific Ocean. In 1998, a wave estimated at nearly 43 m high was measured during the Sydney to Hobart yacht race in the South Pacific Ocean. Although these were the largest waves reliably reported, higher waves undoubtedly occur from time to time. It is not surprising that such extremely high waves have not been measured, since any sailor whose vessel is faced with a 30-m or higher wave has many concerns other than measuring wave height. Most vessels would survive the ride through even the highest wave unless the wave was extremely steep-sided and breaking. A 30-m-high steep-sided wave breaking over the deck of even the largest ocean vessel may be the last wave the vessel ever encounters. Indeed, such large waves may have caused the disappearance of many ships in the past.

So far, the highest waves reliably reported in the Atlantic and Indian Oceans were about 15 m high. However, in September of 2004, the center of **Hurricane Ivan** passed directly over six tide/wave gauges mounted at depths of 60 to 90 m on the Gulf of America (Golfo de México) **continental shelf**. The highest wave measured by these gauges was 27.7 m. The area of highest winds within Ivan did not pass directly over any of the gauges, and it was calculated that the highest wave generated by this storm may have exceeded 40 m. Satellites such as the TOPEX/Poseidon satellite can measure ocean surface heights to an accuracy of within less than 5 cm. Unfortunately, these sensors cannot yet measure the heights of individual waves because the width of their measurement beams is large compared to the distance between ocean wind waves.

Effects of Currents on Wave Height

Steep-sided waves can be created when waves travel in the

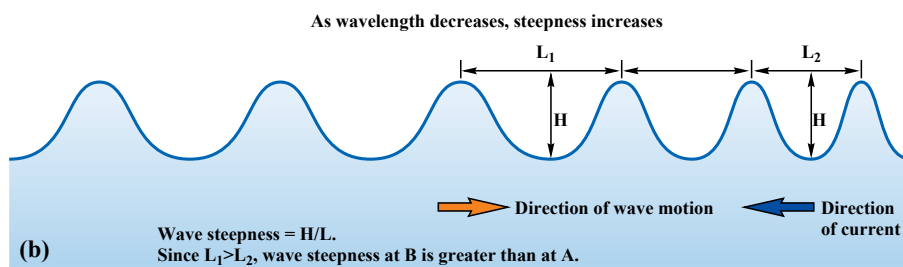
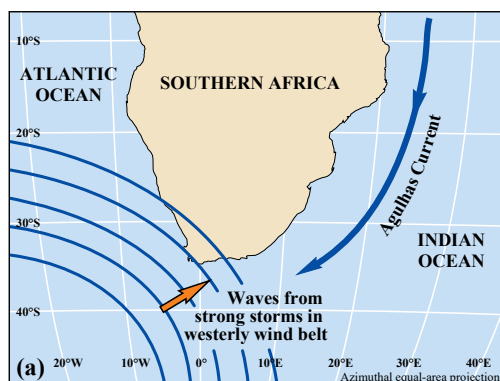


FIGURE 9-8. (a) Waves from around Antarctica travel northward and meet the strong, southward-flowing Agulhas Current. (b) As each wave encounters the current, its forward speed is decreased because the current moves surface water southward, and water particles in each wave are a little farther south after each wave orbit, instead of in their original position. As each wave slows, the following wave that has not yet encountered the current is not slowed, so its crest becomes closer to the crest of the wave preceding it. Hence, wavelength decreases and steepness increases as the figure shows. (c) The tanker *World Glory*, sinking after breaking its back in waves steepened by the Agulhas Current.

direction opposite that of a strong ocean current. The opposition of current and wave motion shortens the wavelength of the waves and increases their steepness, particularly on the front face of the wave. This effect is illustrated in **Figure 9-8**.

In extreme cases, waves can have almost vertical faces. Long-wavelength waves travel faster than vessels. When a vessel encounters a large wave with a nearly vertical face, the vessel may be unable to climb up and over the wave rapidly enough to avoid what is often a fatal plunge under the wave.

Such steep waves occur often in some areas, including where the swift Agulhas Current flows south along the Indian Ocean coast of southern Africa (**Fig. 9-8a, Chap. 8**). Large waves built by Antarctic storms travel north into this area, which is a major shipping lane for traffic between the Indian and Atlantic Oceans and is heavily traveled by oil supertankers. Several ships have been severely damaged or sunk there due to the shortened and steepened waves. In 1968, for example, the tanker *World Glory* broke in two, spilled its entire cargo, consisting of 14 million gallons of oil, and sank after encountering such a wave (**Fig. 9-8c**).

Tankers are constructed with most of the hull weight concentrated in the engine room and crew quarters at the stern, and the anchor-handling and other equipment in the bow. In the middle of the ship, oil is stored in separate compartments held together relatively weakly by the hull. A tanker can break in the middle if it becomes suspended with its center section on the crest of a high, steep-sided wave or suspended between two waves with the bow section on one wave and the stern on the other. Sophisticated satellite-based radar and other sensors now provide accurate advanced wave height forecasts in areas such as the Agulhas Current, so vessels are now able to avoid this region when dangerous waves are likely to be present.

Are Wave Heights Increasing?

Higher waves possess higher energy than lower waves and can create more damage when they impact a shoreline. Therefore, it is important to know whether wave heights are increasing due to higher wind speeds caused by a changing **climate**. However, measuring wave heights is not as simple as just recording the maximum wave height at one location over a period of time. Generally, oceanographers measure a parameter called “significant wave height,” which is a measure of the average height of approximately the highest one-third of all waves within a given area at a specific time. Methods of measuring wave heights have varied in the past several decades, so there are very few long time-series records of wave heights measured by a consistent method. This lack of consistent methodology makes conclusions about long-term trends in wave height difficult.

Wave heights in the North Atlantic Ocean were measured by researchers on a lightship moored off the southwest tip of England during 1960–1985. These measurements showed not only that the maximum wave heights vary widely between years, but also that the maximum wave heights apparently increased from about 12 m to about 15 m, about 25%, over this 25-year period. Since 1985, similar increases in wave heights have been observed in other parts of the Atlantic and Pacific Oceans by other techniques, including measurements of significant wave height by satellite-based sensors, calculation of significant wave heights from historical wind data records, and seismological data. Seismological data can be used because the microscale fluctuations in seismic records are related to the impact of waves on the coastline.

Although wave-height studies have shown that wave heights are increasing in some areas of the Atlantic and Pacific Oceans, they have also shown that wave heights have not increased significantly in other areas of these same oceans. At present, we do not know whether a long-term trend toward higher maximum wave heights is real. If it is real, we do not know whether it is related to climate change, whether the trend will continue, or in which areas this change is occurring. We are also unsure to what extent opposite trends or a lack of change may have occurred in other oceans.

However, we do know that any increase in maximum wave heights must be related to increased wind speeds, storm frequencies, or both. Small changes in ocean surface temperature may cause changes in the ocean-atmosphere interactions that create winds (**Chap. 7**). Hence, if wind speeds or storm frequencies have increased, the changes may be related to enhancement of the greenhouse effect caused by human release of **greenhouse gases (CC9)**. Alternatively, the change in wave heights may be related to a natural long-term climatic cycle. Long-term climatic changes or cycles with periods of 30 years or more are known to occur. For example, historical records for Atlantic hurricanes suggest that they were fewer and weaker during the 1970s through the 1990s than in the preceding decades or in the current millennium (**Chap. 7**).

Considerably more information will be needed to fully iden-

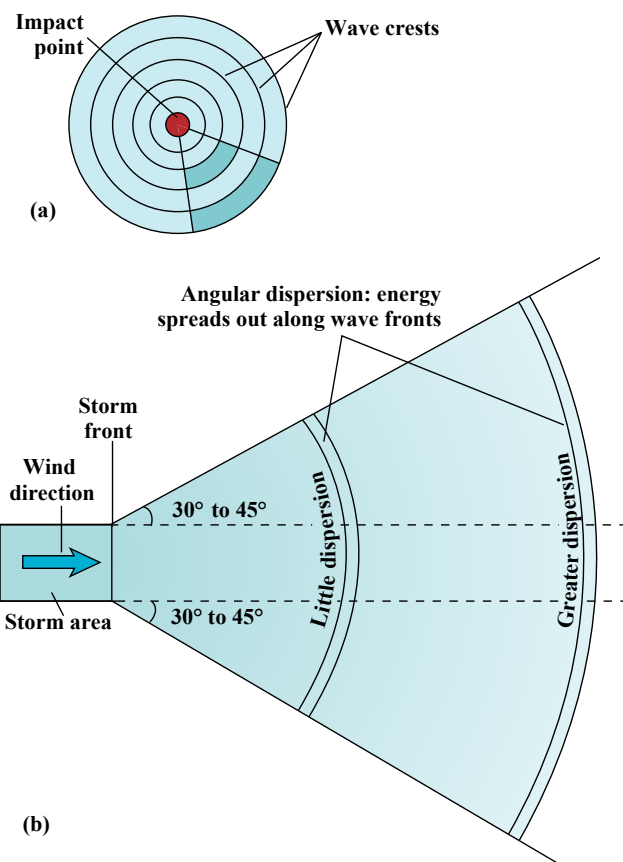


FIGURE 9-9. (a) Waves spread out uniformly in all directions from an impact point, and energy is spread along the increasing length of each wave as it moves away from this point. (b) Waves generated along a storm front travel forward in the direction of the winds in the storm, but they also spread out in a fan shape. This disperses (spreads) the wave energy along a progressively lengthening wave crest with distance from the storm.

tify the trends in wave heights and to determine whether these trends are part of a natural climatic cycle, are related entirely to the greenhouse effect (CC9), or are partially natural and partially related to the greenhouse effect. These issues are important because any long-term trend of increasing wave heights will pose problems for ships and increase coastal erosion.

WAVE DISSIPATION

When the force that creates a wave is removed, the wave continues to move across the ocean surface. For example, waves created by a rock thrown into a lake continue long after the rock's impact, and large waves may crash ashore on days when there is no wind to create them. The reason is that wave energy dissipates (is lost from the wave) very slowly.

Energy is lost from a wave because of viscosity (internal friction) between water molecules moving within the wave and air resistance as the wave moves across the surface, but this energy loss is very small. Frictional loss in a flowing fluid depends on the fluid's viscosity. The viscosity of water is not high (Chap. 5), so frictional loss is a very small fraction of the total wave energy in all but very short-period (<0.1 s) capillary waves. For capillary waves, viscosity is important as a means of dissipating wave energy because such waves contain only a very small amount of energy. In fact, the energy in capillary waves can be totally dissipated by viscosity in a minute or less after the wind stops. Capillary waves, therefore, disappear quickly when there is no wind, but larger waves do not.

Wave steepness diminishes once the wind ceases. Hence, in the open ocean, waves do not break and lose energy through turbulence unless winds blow and add more energy to the sea. Minor exceptions occur when waves encounter winds that blow,

or currents that flow, against the wave's direction of travel. Waves then slow, and wave steepness increases (Fig. 9-8b).

The waves created by a rock thrown into a lake spread in a circular pattern away from the point of impact. This process does not decrease the total energy of each wave. However, as the wave moves out from the impact point, it spreads over an ever-increasing area (Fig. 9-9), and the wave height is reduced. Storm waves also spread out from where they are generated, but some storms generate their largest waves across a broad storm front. The resulting waves travel out from the storm area in the same general direction, and wave energy tends to be concentrated in that direction (Fig. 9-9b).

Because waves lose very little energy as they travel across the ocean surface, most waves travel until they meet a shore, where their energy is converted to heat or used to erode the shore, transport sand along the coast, or create **longshore currents** (Chap. 13). Although breaking waves release a considerable amount of heat energy, this process does not cause a measurable change in water temperature, because water has a high heat capacity (Chap. 5, CC5). In addition, heat from breaking waves is dissipated in very large volumes of water.

DEEP-WATER WAVES

Individual water molecules in waves in deep water (depth $>L/2$) move in vertical circular orbits oriented in the direction of wave travel (Fig. 9-10). The forward motion at the top of the orbit is very slightly greater than the backward motion at the bottom of the orbit, hence there is a very small net forward movement of water in the wave, although this forward movement of water is so small that it is negligible (Fig. 9-10b). Water motion within a wave is not restricted to water depths between crest and

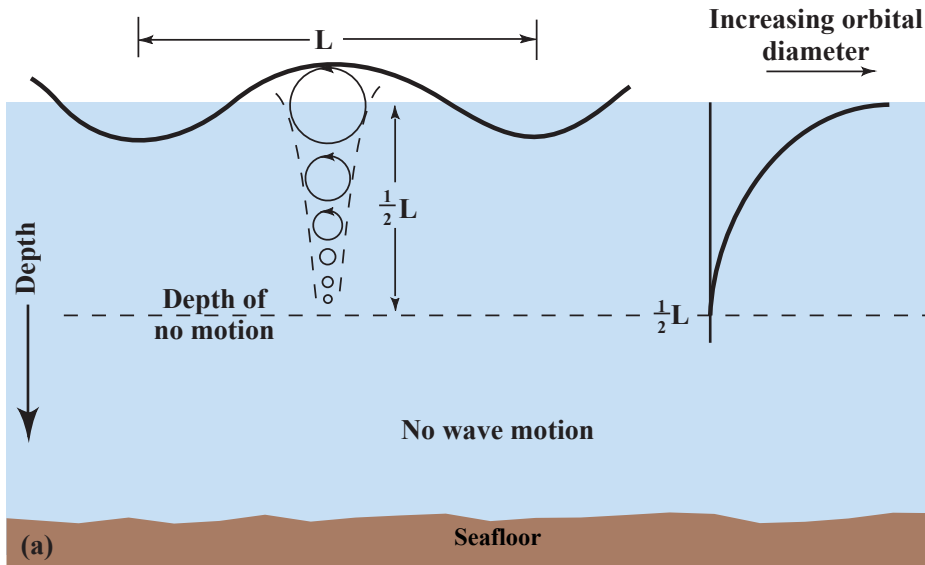
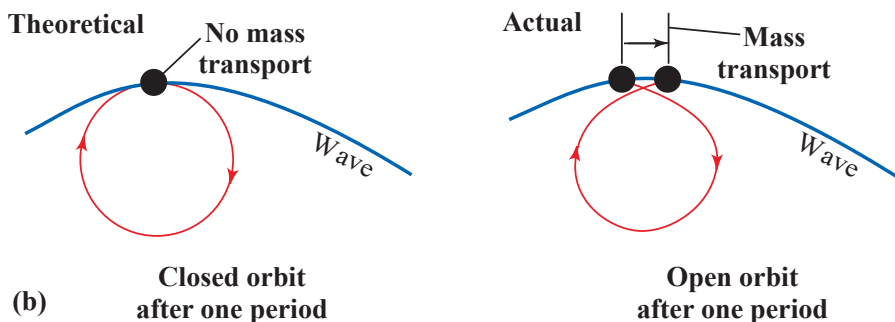


FIGURE 9-10 Orbital motion of water particles beneath waves. (a) The orbits in which individual particles move within a wave decrease in diameter exponentially with increasing depth. The wave motion becomes essentially zero at a depth equal to one-half of the wavelength. (b) The particle orbits are not exactly closed. Instead, each particle moves forward a very small distance (exaggerated in this figure) during each orbit. Therefore, there is a very small net mass transport of water in the direction of the wave.



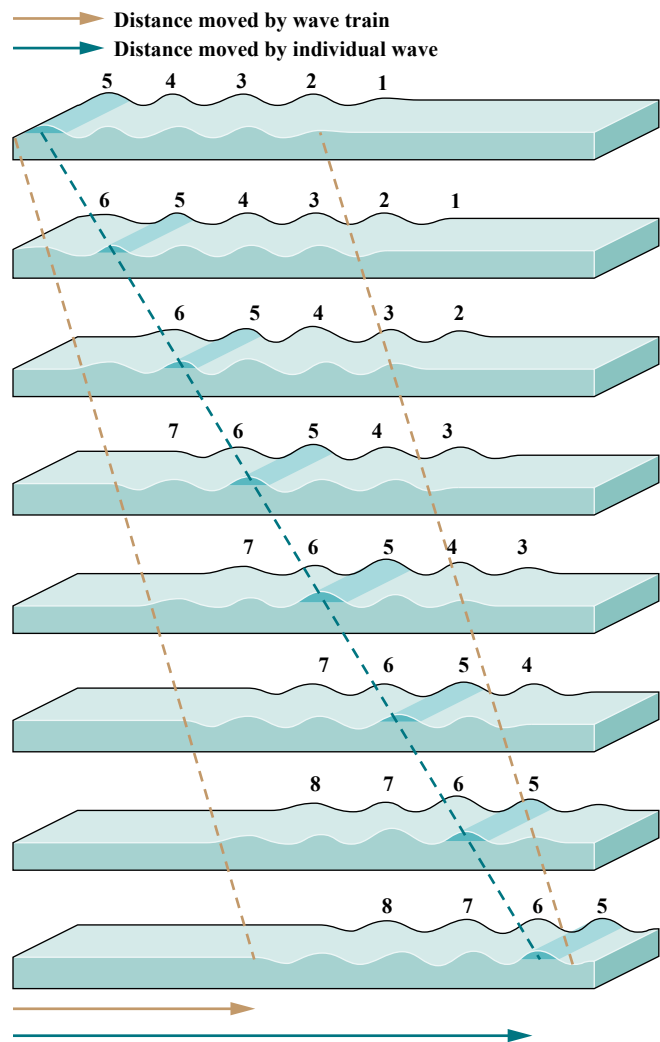


FIGURE 9-11. Waves travel in groups called wave trains. As the leading wave of the group travels forward, it transfers half of its energy forward to initiate motion in the undisturbed surface ahead and transfers the other half to the wave behind it to maintain the wave motion. The leading wave is constantly decaying (losing energy) as it transfers energy forward to displace the undisturbed water surface ahead of it. As a result, the leading wave in the wave train is constantly disappearing, while a new wave is constantly being formed at the back of the train. To visualize this process, follow wave number 5 in this diagram. Notice that the train travels at half the speed of an individual wave.

trough. Scuba divers who have dived where long-period swell waves are present know that the surging wave motion can be felt 10 m or more below the surface, even when the surface swell waves are less than a meter high.

Water immediately below the surface moves in an orbit whose diameter is equal to the wave height, whereas water farther below the surface moves in orbits whose diameter decreases as depth increases. The decrease in orbital diameter with increasing depth depends on the wavelength. The diameter is reduced to one-half of the wave height when the depth is equal to one-ninth of the wavelength, and it is almost zero at a depth of one-half of the wavelength (Fig. 9-9).

The speed of a wave (the speed at which the wave form of the wave moves forward) in deep water also depends on wavelength and is approximated by the following equation:

$$C = \sqrt{gL/2\pi}$$

where g is the acceleration due to gravity. Because g ($9.8 \text{ m}\cdot\text{s}^{-2}$) and π (3.142) are constants, we can simplify this equation to:

$$C = 1.25\sqrt{L}$$

C is measured in meters per second ($\text{m}\cdot\text{s}^{-1}$), and L in meters (m).

TABLE 9-1 Wavelength, Period, Celerity, and Depth of No Motion for Deep-Water Waves

Wavelength		Period	Frequency	Depth of No Motion ($L/2$)		Depth at Which Motion Reduced by 50% ($L/9$)		Deep Water Celerity		
m	ft			m	ft	m	ft	$\text{m}\cdot\text{s}^{-1}$	$\text{km}\cdot\text{hr}^{-1}$	mpg
1.6	5	1	60	0.8	2.5	0.2	0.6	1.6	5.6	3.5
6.2	20	2	30	3.1	10	0.7	2.2	3.1	11	7.0
14	45	3	20	7.1	23	1.6	5.0	4.7	17	10
25	80	4	15	13	40	2.8	8.9	6.2	22	14
39	126	5	12	20	63	4.3	14	7.8	28	17
56	181	6	10	28	90	6.2	20	9.4	34	21
77	246	7	8.6	38	123	8.5	27	11	39	24
100	322	8	7.5	50	161	11	36	12	45	28
126	407	9	6.7	63	203	14	45	14	51	31
156	502	10	6.0	78	251	17	56	16	56	35
225	724	12	5.0	113	362	25	80	19	67	42
306	985	14	4.3	153	492	34	109	22	79	49
400	1287	16	3.7	200	644	44	143	25	90	56
506	1628	18	3.3	253	814	56	181	28	101	63
624	2008	20	3.0	312	1004	69	223	31	112	70
975	3138	25	2.4	488	1569	108	349	39	140	87
1405	4521	30	2.0	703	2261	156	502	47	169	105



FIGURE 9-12. A boat's bow and stern waves travel out from the ship as wave trains. If you look carefully at the bow wave of the leading boat, you can see that the leading wave disappears as it moves away from where the boat has passed and is replaced by another wave behind it. The second wave in turn disappears to be replaced by another one behind it, and so on. The wave energy is also slowly spread as the wave crest lengthens by dispersion, and the wave train eventually disappears. Note how the bow and stern waves of the two boats combine to form complex wave interference patterns.

Thus, the speed of deep-water waves (depth $> L/2$) increases with increasing wavelength. Because wave speed is also equal to L/T , we can calculate the wavelength of a deep-water wave if we know its period:

$$C = L/T = 1.25$$

$$L = 1.25^2 \times T^2 = 1.5625T^2$$

Table 9-1 lists wavelengths and celerities for deepwater waves of different periods. The table can be useful for scuba divers in planning a dive. If the divers count the number of waves that pass their boat per minute, they can calculate the average wave period. From **Table 9-1**, they can then determine the $L/2$ and $L/9$ depths for this wave period. If the $L/9$ depth exceeds the depth of the planned dive, the divers can expect to feel a strong wave surge, though it will be less than that at the surface, throughout the dive. At depths greater than $L/2$, there will be no wave surge.

Wave Trains

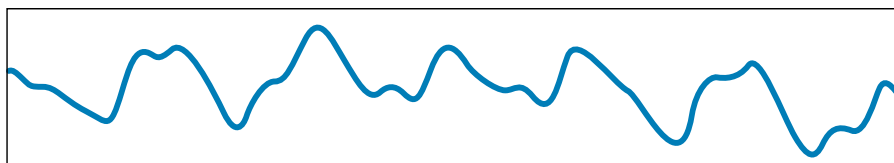
Waves usually travel in groups called “wave trains.” As the leading wave in a wave train travels, some of its energy is transferred to the molecules of undisturbed water in front of it. This energy is used to initiate orbital motion of the previously undisturbed water molecules. However, only half of the energy of the individual wave is transferred forward; the remaining energy

is transferred back to the second wave in the train. By examining the pressure gradient under the wave, we can see how this happens (**Fig. 9-4**). The second wave in the train also transfers energy forward to the first and back to the third wave. As the wave train progresses, energy is lost from the front wave of the wave train. The front wave progressively loses height and eventually disappears. The energy transferred backward from the first wave is transferred progressively rearward from one wave to another, until it passes the last wave and builds a new wave at the rear of the wave train.

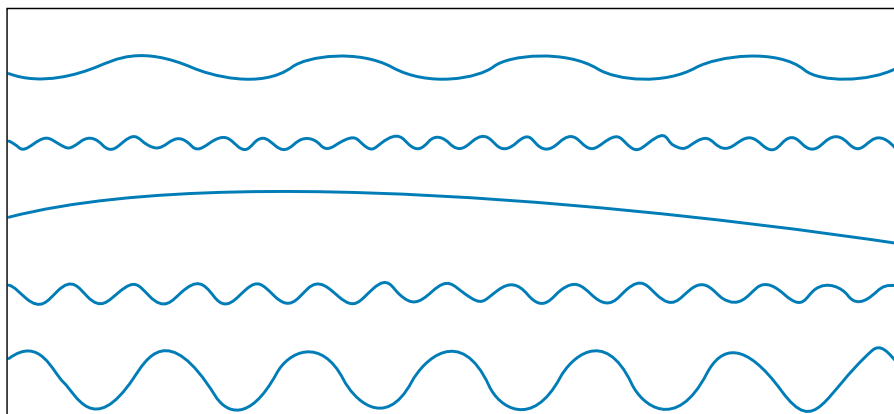
In deep water, a wave train and the energy associated with it move at one-half the speed of individual waves within the wave train. The time it takes for waves of a particular wavelength to cross the ocean must be calculated from this group speed, which is one-half of the individual wave speed specified in **Table 9-1**.

As a result of the rearward transfer of energy in the wave train, the front wave in the train continuously decays, and a new wave is continuously created at the rear of the train (**Fig. 9-11**). Individual waves form at the back of the train progress forward as their predecessors decay and, eventually, reach the front of the train, where they decay themselves. We can see this process by carefully watching ripples caused by a stone thrown into a lake or the waves of a ship's wake (**Fig. 9-12**).

Wave Interference

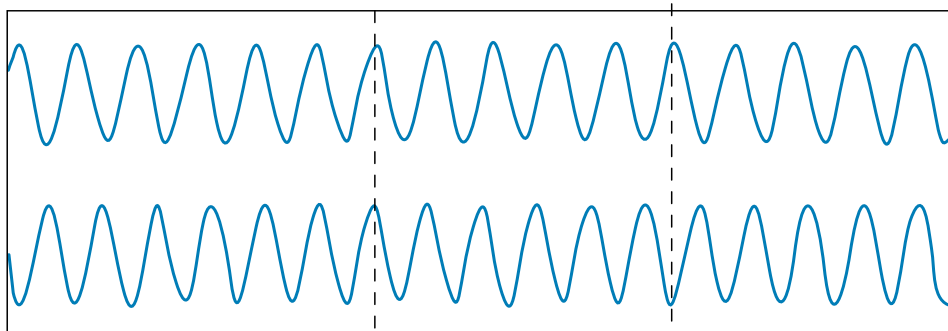


(a) Waveform generated by interference (addition) of component waves

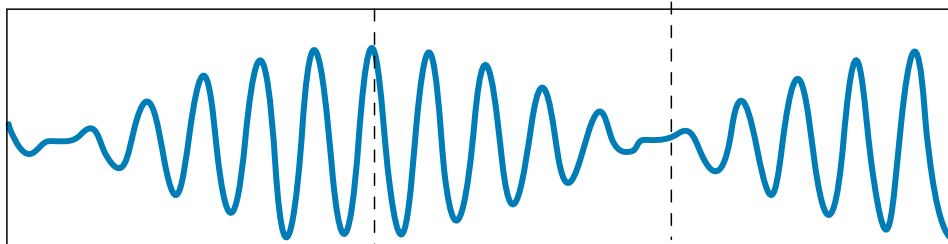


(b) Component waves

FIGURE 9-14. When two sets of waves of very similar wavelengths arrive at the same location at the same time, their addition can produce large, long-period variations of the wave height in the resulting waveform. (a) These two simple waves have slightly different wavelengths. (b) When they are combined, they produce a very different waveform. This is why we may see periodic sets of very much higher (and lower) waves than normal arriving at the shore.



(a) Component waves



(b) Waveform generated by interference (addition) of component waves

Only very rarely are waves in a specific part of the ocean regularly spaced and all of the same height. The reason for the irregularity in height and spacing is that waves of several different periods and moving in different directions pass a given location simultaneously. If we plot the sea surface height as a function of time, we get the type of complicated wave pattern shown in **Figure 9-13a**. Surprisingly, the pattern in **Figure 9-13a** is simply the sum of the five simple waves shown in **Figure 9-13b**.

When wave trains of similar wave heights but slightly different periods arrive at the same time, the sea surface will appear to alternate between periods of low and high waves. During relatively calm periods (the segments where the waveform depicted in **Figure 9-14b** is almost flat), the crest of one wave arrives at almost the same time as the trough of another wave, and the elevations of the two waves cancel each other out (**Fig. 9-14**). During the intervals when the waves are high, the crests of the two waves arrive at the same time and combine to form a larger

wave (**Fig. 9-14**). When waves of several different, but similar, periods arrive simultaneously, the situation is more complex. However, the process of wave addition and subtraction, called “wave interference,” is what causes waves to vary in height in irregular patterns..

The irregular pattern of waves caused by wave addition is important to surfers, who await sets of big waves. Contrary to some popular beliefs, the periodicity in wave heights does not always follow a consistent pattern. Sets of waves that are especially high may appear every few minutes or only every few hours at any given location on any day. People who visit coastlines when the sea is rough should be aware of this phenomenon. It is not safe to assume that a dry position on the rocks or beach is beyond the reach of the waves. More than a few unfortunate individuals are washed off the rocks or swept off beaches and drown every year because they have made that assumption. It is wise always to anticipate that waves much larger than those that have arrived in

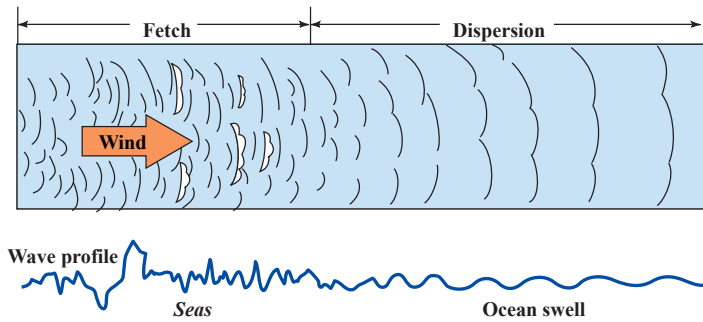


FIGURE 9-15. Within the fetch of a storm, the waves are irregular because they are the sum of many separate waves of different wavelengths, as shown in Figure 9-12. Long-wavelength waves move faster than shorter-wavelength waves, such that, as waves move away from the storm, the long-wavelength waves move ahead of the shorter-wavelength waves. This sorting of the waves by wavelengths is called wave dispersion. Because they are separated by wavelength, the waves appear to become smoother as they travel away from the storm fetch. The greater the distance from the fetch, the greater the difference in the arrival times of waves of two different wavelengths.

the preceding hours might suddenly appear.

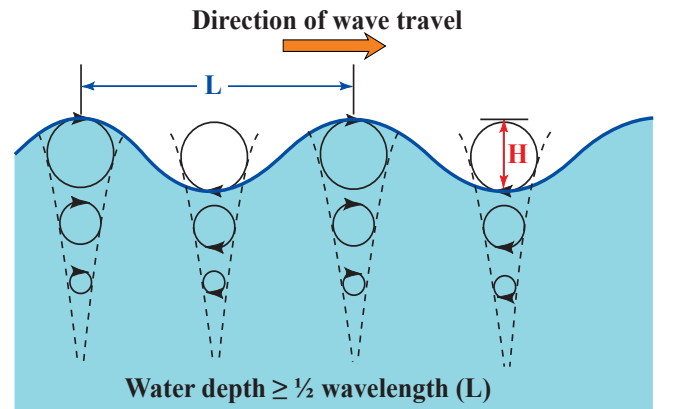
Wave Dispersion

Storms create waves with a wide range of periods. The speed of deep-water waves increases as period (and wavelength) increase (**Table 9-1**). Hence, waves with longer periods and longer wavelengths travel faster than shorter-period waves, and longer-period waves move away from the area where they were generated more rapidly than shorter-period waves do. Wave trains of different periods become separated as they move away from the storm center where they were created (**Fig. 9-15**). This phenomenon is called “wave dispersion” and causes waves to be sorted by period (and wavelength). Because waves are sorted by period as they move away from their origin, the longer-period waves from a storm arrive at locations far from the storm before the shorter-period waves do. If the storm that created the waves occurred about 100 km away, waves with a 5-s period will arrive about 3 h after waves with a 10-s period. If the storm occurred about 1000 km away, the 5-s waves will arrive about 36 h after the 10-s waves. The waves from the more distant storm will have traveled farther and been dispersed by wavelength to a greater extent (**Fig. 9-15**).

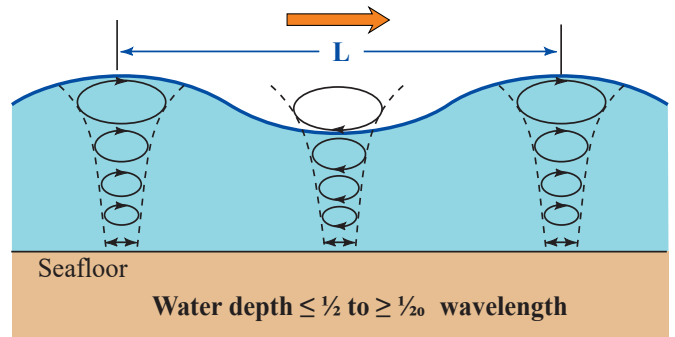
Normally, waves of more than one storm arrive simultaneously, so the shorter-period waves from any given storm are usually obscured by longer-period waves from another storm. The shorter-period waves can be observed if detailed wave records are analyzed mathematically. Oceanographers are able to calculate the locations of storms many thousands of kilometers away by analyzing waves arriving at two or more locations. The wave dispersion at each location reveals the distance of the storm from that location, and the distances of the storm from two widely separated locations will reveal the storm location. For example, storms near Antarctica can be located by wave measurements made in locations such as the United Kingdom and Brazil. Although this method is reliable, satellite observations of cloud patterns are now a much easier way to locate storms.

As waves disperse by wavelength in their direction of travel, wave steepness decreases because the waves also spread laterally, and their energy is distributed over a wider area. The reduction in steepness is accompanied by a change in the wave shape, making it closer to the ideal smooth sine wave shape (**Fig. 9-2a**). Thus, at some distance from the area where they are generated,

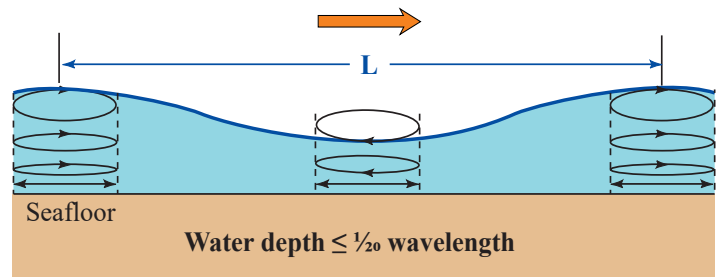
the waves are sorted by wavelength and form a swell—smooth undulations without sharp or breaking crests (**Fig. 9-15**). A swell originates from a sea and is caused by the combination of wave (wavelength) dispersion and lateral dispersion of wave energy (spreading of the wave front like the spreading of a ripple as it moves away from the point of impact of a stone) as the waves travel from their origin.



(a) Deep-water wave



(b) Intermediate wave



(c) Shallow-water wave

FIGURE 9-16. Effects of water depth on waves. (a) In waves traveling across the ocean where the water depth is greater than one-half of the wavelength, the orbits of water particles in the wave are circular and wave speed is determined only by the wavelength. (b) Where the water depth is less than one-half but more than one-twentieth of the wavelength, wave motion is slowed and distorted by friction with the seafloor, and the particle orbits are flattened into ovals. (c) Where the water depth is less than one-twentieth of the wavelength, the particle orbits are flattened so much that they become nearly horizontal, back-and-forth motions. In this case, the wave speed is determined only by the depth. Note that each part of the figure does not depict a single wave moving into shallower water. As explained later in the chapter, wavelength is progressively shortened once a wave enters shallow water and becomes an intermediate or shallow water wave. Also, the wave height decreases somewhat when it is an intermediate wave and then increases rapidly once it becomes a shallow water wave and moves into progressively shallower water.

WAVES IN SHALLOW WATER

On a calm-wind day at the shore, when there is a swell from a distant storm, we observe that offshore in deep water, the waves roll smoothly toward the shore without breaking. Once they reach shallow water, the same waves form breakers. Clearly, something happens in shallow water that alters the behavior of waves.

Interaction with the Seafloor

When waves enter water shallower than half their wavelength ($L/2$), they begin to interact with the seafloor. The wave motion becomes inhibited because the solid seafloor prevents water molecules from moving in circular orbits. Molecules immediately above the seafloor can move only back and forth. As a result, the orbits of water molecules within the wave are distorted into elongated ellipses (Fig. 9-16). Compression of the orbits and friction between water and seafloor slow the forward motion of the wave.

As water depth decreases between $L/2$ and $L/20$, the forward speed of the wave decreases progressively (Fig. 9-17). The equation used to calculate the speed of waves when they are in water depths between $L/2$ and $L/20$ is somewhat complex. In these depths, waves are called intermediate waves. In contrast, at water depths of $L/20$ or less, the wave speed is controlled only by water depth. Waves in water depths less than $L/20$ are called shallow-water waves. The speed of shallow-water waves is given by the equation:

$$C = \sqrt{gD} = 3.13 \sqrt{D}$$

where C is the celerity ($\text{m}\cdot\text{s}^{-1}$), D is the depth (m), and g is the acceleration due to gravity ($\text{m}\cdot\text{s}^{-2}$). Thus, all waves, regardless of their period, travel at the same speed when they are in water of the same depth, provided that the depth is less than $L/20$. Because wavelength and period are related, longer-period waves will

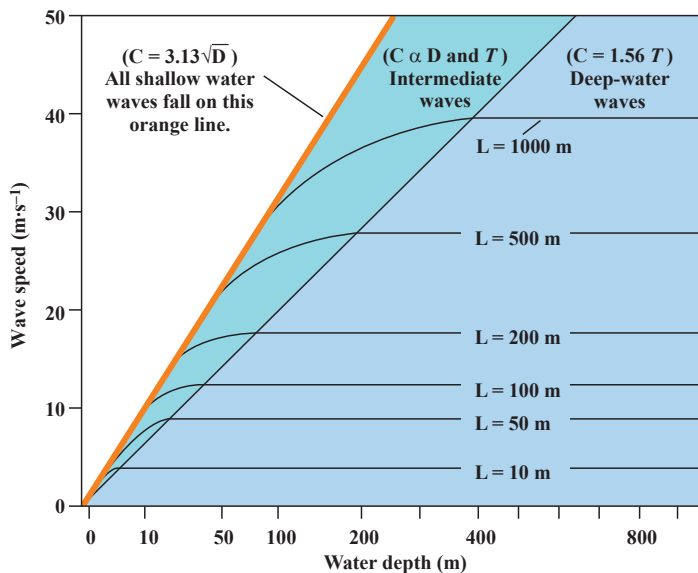


FIGURE 9-17. The speed (or celerity, C) of a deep-water wave is constant and depends on the wavelength (or wave period). For example, a deep-water wave of wavelength 1000 m has a speed of almost exactly $40 \text{ m}\cdot\text{s}^{-1}$. The speed of shallow-water waves is determined only by depth and decreases as water depth decreases. To determine the speed of a shallow-water wave in this figure, simply find the speed on the orange line that corresponds to the water depth. The speed of intermediate waves is determined by both water depth and wavelength. For example, the speed of an intermediate water wave of wavelength 1000 m decreases from almost exactly $40 \text{ m}\cdot\text{s}^{-1}$ when the water is 400 m deep, to a little more than $30 \text{ m}\cdot\text{s}^{-1}$ when the depth equals one-twentieth of the wavelength (50 m) and the wave becomes a shallow-water wave.

become shallow-water waves in deeper water than short-period waves do (because $L/20$ is greater when L and T are larger).

As waves enter shallow water and are slowed, their period does not change. Because wave speed is the ratio of wavelength to period ($C = L/T$) and the period does not change, the wavelength must decrease as the speed decreases (Fig. 9-17). We can easily see why the wavelength decreases if we consider what happens to two successive waves following each other into shallow water. The first wave enters shallow water and is slowed before the second wave. The second wave comes closer to the first wave because it does not slow until it also reaches the shallow water. As they move into shallower water, both waves continue to be slowed, but the first wave continues to be slowed sooner than the second wave, which is always in deeper water. Therefore, the wavelength decreases progressively as waves move into shallower water and wave speed continues to decrease (Fig. 9-17). As wavelength decreases, wave steepness increases (Fig. 9-8).

Wave Refraction

Waves usually approach a shoreline at an angle. Consequently, because one end of the wave-crest line enters shallow water and slows while the rest of the wave is still in deeper water and traveling at its original speed, the wave is **refracted**, or bent (Fig. 9-18a). Lines perpendicular to the crest lines of successive waves in Figure 9-18a show the path that a specific point on the wave crest follows as it moves inshore. These lines are called **wave rays** or “orthogonals.” As the wave continues to move inshore, more of the wave enters shallow water and slows. However, the section of the wave that first entered shallow water is still moving into progressively shallower water and slowing further, so wave refraction continues.

Note that the wave rays bend toward shallower water. As the refraction process continues to bend the wave, the wave crests tend to become aligned parallel to the shore. The refraction is seldom complete, so a wave crest rarely reaches the shore or breaks at precisely the same time along its entire length. However, even if waves approach the shore at a large angle, they are refracted and always reach the shore almost parallel to it (Fig. 9-18a).

If waves move into shallow water where seafloor ridges or depressions are present, the parts of each wave where the water is shallower slow down, while other parts in deeper water do not. Thus, the refraction pattern differs from the simple pattern depicted in Figure 9-18a. In many areas, seafloor **topography** immediately offshore is a continuation of land topography. For example, many coastlines have horseshoe-shaped bays where valleys reach the shore (Fig. 9-18b). The valley often continues offshore from the center of the bay, and the seafloor falls away in a valley-shaped depression between submerged ridges that extend out from the bay’s headlands. Most bays of this type have a horseshoe-shaped sandy beach at the center and rocky headlands at each end (Fig. 9-18b). As we shall see, the headlands are rocky, and the bay’s interior is sandy because of the wave refraction.

Figure 9-18b shows the locations of successive wave crests as waves move toward a bay. As a wave approaches shore, the first part of the wave to encounter shallow water will be that over the undersea ridge extending out from the headland closest to the direction from which the wave arrives. While this part of the wave slows, the rest of the wave continues at its original speed. Then another part of the wave slows where it encounters the submerged ridge extending from the second headland. Thus,

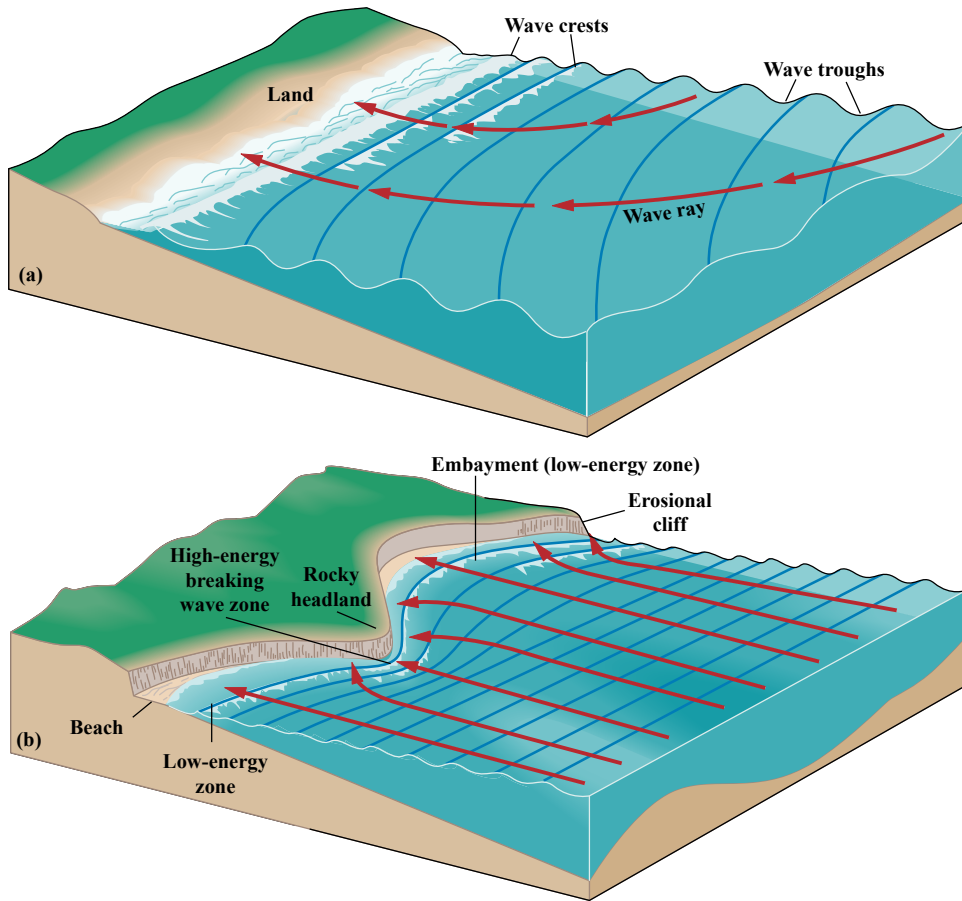


FIGURE 9-18. Wave refraction. (a) Waves generally approach the coastline at an angle. Consequently, part of the wave front reaches shallow water and is slowed before the rest of the wave. It continues to slow as the other parts of the wave move more rapidly toward shore until they, too, are progressively slowed. As a result, the wave front is bent and becomes aligned more closely parallel to the beach. The path followed by any point on the wave crest is called a wave ray. (b) As a wave approaches a bay flanked by headlands whose topography extends onto the offshore seafloor, the first parts of the wave to slow are those over the underwater extensions of the headlands, and the last part to be slowed is that over the deeper water at the center of the bay. Thus, the wave is refracted, and wave energy is concentrated on the headlands and spread out inside the bay. Breaking waves are the strongest at the headlands.

while parts of the wave are slowed at each headland, the rest of it continues at its full speed into the center of the bay. As the wave front enters the bay, the center section travels farther in deep water than the parts that enter the bay at each side. The wave is refracted so that it breaks at almost the same time along the entire length of the beach. Note again that the wave rays always bend toward shallower water.

Refraction redistributes the wave energy. In deep water, the wave has the same amount of energy per unit length along the entire length of its wave crest. As the wave is refracted in a bay, the total length of the wave crest is increased (**Fig. 9-18b**), and the same wave energy is distributed over this greater length. Lengthening of the wave crest also results in a lowering of the wave height. In contrast, at a headland, refraction reduces the length of the wave crest and, consequently, increases the wave energy per unit area and the wave height.

Refraction focuses wave energy on headlands while spreading wave energy along the beach within the bay. This is why we generally swim on the beach near the center of the bay and not at the headlands. The same wave that breaks gently at the middle of the beach smashes violently at the headland. This is also the reason we should exercise caution while walking on rocks of a headland. The headland is where waves are highest and crash most violently ashore. In addition, on narrow headlands where the bottom topography is appropriate, a single wave with the right period that approaches from the right direction may be refracted to hit the headland simultaneously from two directions (**Fig. 9-18b**).

The wave refraction that concentrates wave energy at headlands and spreads energy within a bay determines the character of the shore at these locations. At the headlands, where wave energy is focused, sand does not accumulate because it is carried away

by the wave action, and the shore is steadily eroded. In contrast, within the bay, gentler wave action transports sand toward the shore, where it builds and maintains a beach (**Chap. 11**).

In areas where the seafloor has complex topography with offshore rocks, ridges, and depressions, wave refraction can be far more complicated than the simple patterns depicted in **Figure 9-18**. Sometimes we can tell where such underwater features are by carefully watching wave refraction patterns from a beach or headland.

Breaking Waves

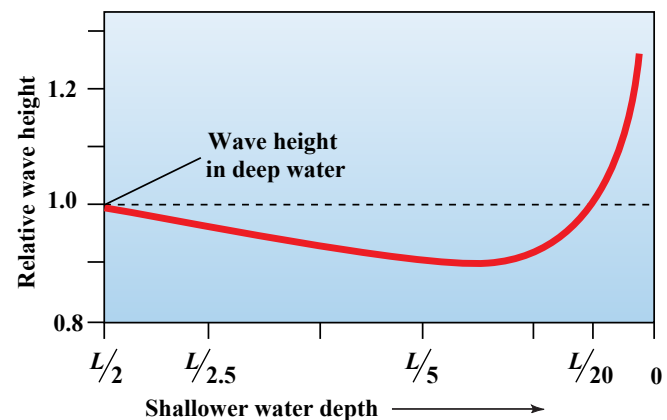


FIGURE 9-19. Wave height changes as a wave moves into progressively shallower water. The wave height declines slowly until the water depth is about one-tenth of the wavelength, then increases rapidly as depth decreases. Most waves become unstable and break before their height is much greater than it was in deep water (usually before the wave height exceeds 1.1 times its height in deep water). However, very long-wavelength waves, such as tsunamis, may be dramatically increased in height before they break.

When waves enter shallow water and interact with the sea-floor, their height is altered by the interaction. At first, the wave height is reduced slowly as the water depth decreases below $L/2$. This loss in wave height is caused by flattening of the orbital paths of water molecules in the wave (Fig. 9-16b). However, in water depths of about $L/10$ and less, the trend reverses and wave height increases rapidly as water depth decreases (Fig. 9-19). The reason is that wavelength decreases as water depth decreases, each wave is “squeezed” by its neighbors, and kinetic energy is converted to potential energy.

Wavelength decreases faster than wave height as water depth decreases below $L/2$. Hence, wave steepness increases (H decreases but L decreases more rapidly, and H/L therefore increases). The speed and wavelength continue to decrease in water shallower than $L/20$ as the wave becomes a shallow-water wave (Fig. 9-17), but wave height increases (Fig. 9-19), wave

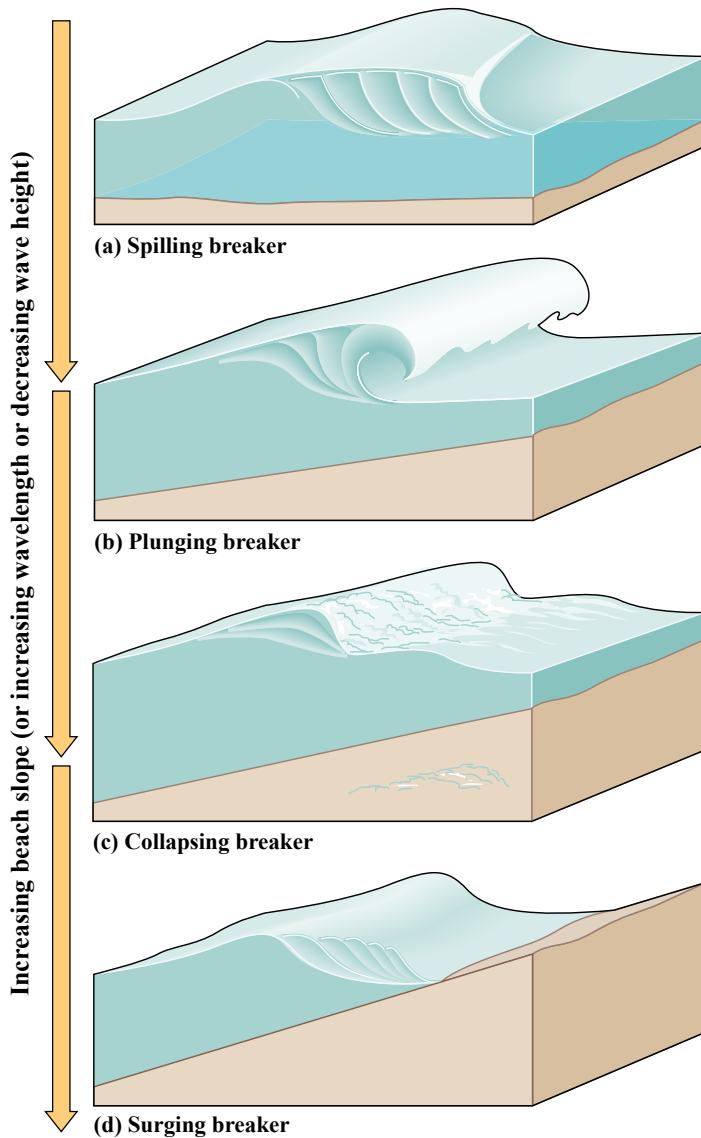


FIGURE 9-20. Breaking waves. (a) The peak of a spilling breaker becomes oversteepened, and it breaks by spilling water from the crest down the front face of the wave. (b) The peak of a plunging breaker travels fast enough to outrun the rest of the wave, and the crest curls over and smashes down on the front of the wave. (c) The base of the front side of a collapsing breaker becomes unstable before the crest, and the front face of the wave collapses. (d) A surging breaker never really breaks. The front face of the wave simply surges up and down on the beach, and the wave energy is partially reflected back out to sea.

steepness increases more rapidly as depth decreases (H increases, L decreases, and H/L increases rapidly), and wave shape is much modified.

Wave steepness increases until the wave becomes unstable and breaks. Wave heights and wavelengths vary among waves reaching the shore at any one time. Waves that follow each other, therefore, become unstable and break at different depths and thus different distances from shore. The area offshore within which waves are breaking is called the **surf zone**.

Although waves are refracted as discussed above, waves rarely reach the shore from a direction exactly perpendicular to the shoreline, and the seafloor rarely has exactly the same slope along the entire shoreline, so almost always one part of a wave breaks before another. A wave often breaks progressively along the crest of the wave as each part of the crest moves into water shallow enough to cause the wave to break.

Waves break in different ways that depend on several factors, including wave period, wave height, and the slope of the ocean floor. These factors determine how quickly the wave becomes oversteepened and unstable.

Spilling breakers are formed when the seafloor over which the wave is traveling is almost flat. When a wave reaches a water depth of about 1.2 times its wave height, it becomes unstable and the crest begins to tumble down the forward face of the wave (Fig. 9-20a). The forward face fills with churning, turbulent water and air bubbles that we see as a white foam. As the wave continues inshore, wave steepness increases slowly because of the almost flat seafloor, but as water spills off the wave crest, it reduces wave height and steepness. The spillage occurs fast enough to maintain the wave at its critical steepness against the tendency for the shallowing water to increase the steepness. Thus, spilling breakers break progressively as they travel inshore. Wave height is reduced progressively by the spilling action as the water depth decreases, until finally the turbulent wave crest encounters the seafloor and wave motion ends.

Plunging breakers are the spectacular curling waves that many surfers covet (Fig. 9-21). They form when the seafloor slope is moderately steep. When the wave reaches the depth at which it becomes unstable, the bottom part of the wave is slowed more quickly than the upper part can slow or spill. Thus, the bottom of the wave lags behind as water in the wave crest outruns it while still traveling in its wave orbit. As a result, the wave crest curls over in front of the wave and plunges downward until it crashes into the trough preceding the wave (Fig. 9-20b).

Collapsing breakers, which are relatively rare, occur where the seafloor has a steep slope, and the lower part of the wave is slowed so rapidly that the leading face of the wave collapses before the crest arrives. As the wave breaks, foam and bubbles are concentrated at the base of the forward face of the wave, and the crest collapses behind, usually with little splash (Fig. 9-20c).

On very steep shores, waves may appear not to break at all. The waves simply surge up and down a very steep beach with little bubble production (Fig. 9-20d). Surging breakers are rare, but the very small, gentle waves that lap onto some beaches in very calm conditions behave somewhat like surging breakers because even a flat beach has significant slope in relation to the tiny wave height. Surging breakers do not break up in foam and bubbles because most of the wave energy is reflected by the steep shore face.

Waves are reflected off vertical or nearly vertical solid objects

FIGURE 9-21. This surfer is riding in the tube formed by a plunging breaker in the north end of the Banzai Pipeline, the famed North Shore surfing area of Oahu, Hawaii.



such as cliffs or **seawalls** with little loss of energy, just as light is reflected by a mirror. When waves are reflected, they pass through and interfere with the incoming waves. Wave patterns created by such reflection can be very complex and are of great concern to engineers who build harbors, marinas, and other coastal structures. Waves are also diffracted by solid objects. Diffraction occurs when part of a wave is blocked by a solid object and the edge of the remaining wave spreads out after passing the object (**Fig. 9-22**).

Often, we see waves breaking at some distance from shore. Reduced in height, the same waves continue toward shore until they break again near the water's edge. This pattern indicates that the seafloor is shallower in the offshore surf zone than it is just inshore of that area. In tropical locations, the shallow area is commonly a fringing **coral reef** (**Chap. 13**). In other locations, it is a **longshore bar** (**Chap. 11**). **Fringing reefs** and long-shore bars are aligned parallel to many coastlines. They help to protect coasts from erosion by waves because they dissipate some wave energy, particularly from the highest and most energetic waves, before they reach the shore.

Surfing

To surf a wave, surfers must propel themselves forward on the board to join the wave motion just at the point where the wave becomes unstable and begins to break. They must position themselves on the forward face of the chosen wave and point the board “downhill.” If the surfers “catch” the wave correctly, they will move forward with the wave. In the correct location, surfers are balanced such that their tendency to fall down the wave because of gravity is just offset by the pressure on the board from the water pushing upward in its orbital motion. Therefore, they must place the board where water is moving upward into the breaking crest. Plunging breakers (**Figs. 9-20b, 9-21**) provide unique conditions for surfing because most of the front face of the wave is traveling upward and then forward to join the curling crest.

Many surfers believe the best surfing is found where waves

approach the shore from a large angle. In such places, refraction does not align the waves exactly parallel to the shore before they break. A wave breaks progressively along the crest as each section reaches shallow water. Surfers simply ride laterally along the wave crest. They remain on the section of the wave crest where the forward face of the wave is moving upward in its last orbital motion before breaking. Where plunging breakers break in this way, surfers can ride under the wave crest in the tube formed where the crest plunges forward ahead of the lower part of the wave (**Fig. 9-21**).

Humans are not the only animals that enjoy riding the orbital motion of waves. Porpoises ride ships’ bow waves by positioning

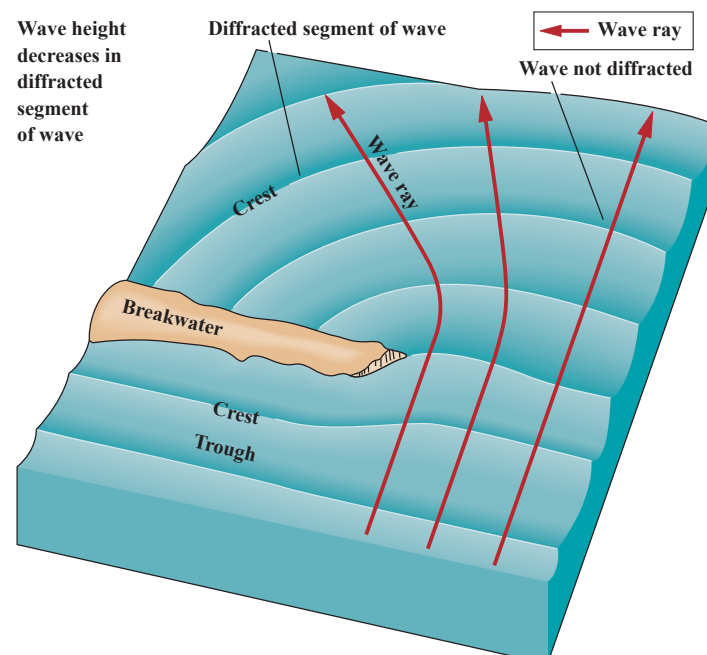


FIGURE 9-22. A wave is diffracted when the wave crest encounters a solid object, such as a breakwater. The part of the wave that passes by the end of the breakwater is bent such that the wave spreads out behind the breakwater.

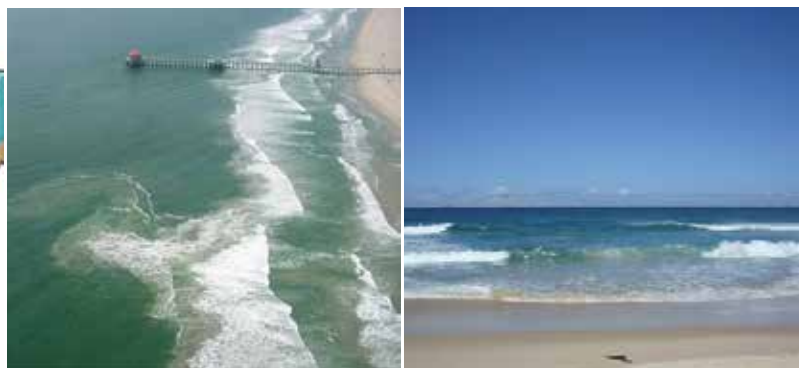
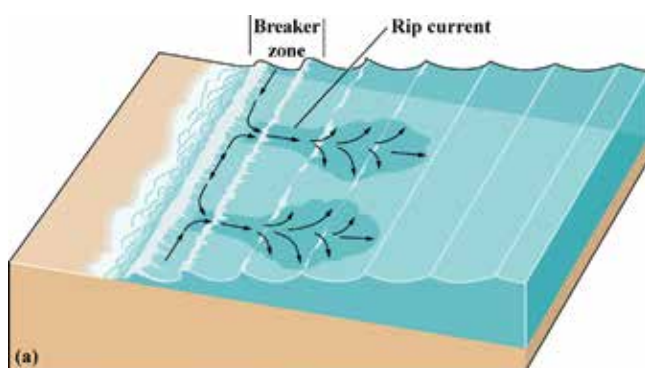


FIGURE 9-23. (a) Rip currents are fast, narrow currents that return water offshore after it has been transported toward the beach that form at intervals along a beach. (b) Rip currents are sometimes visible as foam or discoloration of the water caused by sediments suspended by turbulence in the swiftly moving current. This type of rip current is not in a fixed location on the beach and may appear quickly and dissipate just as quickly. (c) A more permanent type of rip current may form where water runs through a channel on the seafloor. This type can often be seen as a gap in the breaking crests of the waves.

themselves where the water in the bow wave is moving forward in its orbital motion. They often ride this way for hours, “pushed” along by the ship.

Surf Drownings and Rip Currents

Unfortunately, many people drown while playing or swimming in the surf. Drownings are often blamed on “undertow” that supposedly sucks unwary individuals underwater away from the beach. However, “undertow” does not exist. People drown because of two simple phenomena, each of which can be easily avoided or escaped. When large waves break very close to the beach, the force of a wave can easily knock over a person who walks out into the surf. Once knocked over by a wave, an unwary individual may be washed seaward as the water flows back down the beach from the collapsed wave. The person is then at a place where the next wave crashes down. This wave washes the person first toward and then away from the beach as it breaks and the water runs back. In these circumstances, many people simply panic and drown because they cannot recover their balance and stand up.

If you find yourself in this situation, you will not drown if you follow two simple rules. First, grab a breath each time a wave has passed, before you are hit by the next one. Second, use the waves to your advantage. Let a wave carry you inshore. When your inshore motion ceases, do not try to stand up. Instead, either dig your hands and feet into the sand or start crawling toward the beach as you grab that next important breath. As each new wave arrives, let go and allow it to carry you farther inshore. If you take this approach, you will soon be sitting safely on the beach telling others how much fun you had playing in the surf. If you are a good swimmer, an alternative is to swim out beyond the breaking waves, where you can float comfortably and rest before swimming back to shore or calling for help.

The second major cause of beach drownings is **rip currents** (often incorrectly called “rip tides”). Waves create a small but significant net movement of water in the direction of wave travel (Fig. 9-10b). This net forward movement is increased in the surf zone because water in the wave crest outruns water in the wave trough as the wave breaks. Accordingly, in the surf zone, water is continuously transported toward the beach. However, it cannot simply accumulate on the beach, but must flow back through the surf zone. When the waves approach the beach at an angle, as they usually do, water that is transported onto the beach is also transported along the beach in the direction of the waves. Eventu-

ally the water encounters an area where it can flow back out as a rip current through the surf zone against the waves more easily than it can continue to accumulate and flow along the beach (Fig. 9-23a). In such areas, wave heights are generally somewhat smaller because a depression or shallow channel runs offshore from the beach.

The corridors in which water flows away from the beach are usually narrow and may be spaced well apart. The rip currents that flow offshore through these corridors consist of all the water that was transported onshore over a broader width of beach (Fig. 9-23). Because large amounts of water are moving through the narrow corridors across the surf zone, the flow rate or current through the return corridors can be fast.

Swimmers who enter a rip current will find themselves carried rapidly out into deeper water by the current. A rip current can be so fast that even the most accomplished swimmer cannot swim against it back to the beach. Tragedies occur when a panicked swimmer tries to fight the rip current, becomes exhausted, and drowns. However, even poor swimmers can easily avert such tragedies if they understand that rip currents are narrow, often only a few meters wide. A swimmer who meets a rip current should turn and swim parallel to the beach. A few strokes will bring the swimmer out of the rip current to an area where it is easy to swim safely ashore. A less desirable alternative is simply to ride with the rip current until it stops, usually only 200 or 300 m offshore, and then signal for help.

The locations of rip currents cannot always be seen easily, particularly by a swimmer in the water, but they are most likely to occur where depressions run down the beach into the surf. Rip currents may reveal themselves in plumes of increased turbidity (Fig. 9-23b), reduced wave heights in the surf zone, or, occasionally, as lines of floating debris or foam moving offshore.

TSUNAMIS

Although tsunamis are relatively rare and most tsunamis are small enough to cause no harm, a large tsunami can be devastating. For example, the December 2004 tsunami caused the deaths of many thousands of people around the Indian Ocean, and the March 2011 tsunami also killed thousands in Japan. Tsunamis as large as these are not frequent events but most people do not know that far bigger tsunamis have occurred in the past and will occur again.

Tsunamis can be generated when an earthquake or volcanic eruption moves a section of seafloor or coast, when a meteor-

ite or coastal land collapse impacts the sea surface, or when an undersea landslide takes place. Each of these events can produce an abrupt displacement of the ocean water that causes the water column to oscillate, generating waves that generally have much longer periods than wind waves. Tsunamis are not related to tides, but they are often incorrectly called “tidal waves.” Tsunami is a Japanese word that is translated as “harbor wave,” but tsunamis are definitely not restricted to harbors.

Not all undersea earthquakes, volcanic eruptions, or landslides cause tsunamis. Tsunamis are most likely to be created when such seismic events cause a section of seafloor to move vertically or to slump. The sudden vertical movement either pushes up the seafloor and overlying water to form a wave crest or lowers the seafloor and overlying water to form a wave trough. The event may cause only one, almost instantaneous, vertical movement of the seafloor. Nevertheless, a series of several waves is created as the water oscillates before returning to a level configuration. This series resembles the waves created by a stone thrown into a pond, radiating outward from the stone’s impact point. Hurricanes and **extratropical cyclones** can cause a different phenomenon, called a **storm surge**, that elevates the sea surface and may cause flooding and damage similar to that caused by tsunamis. These storm surges are not considered to be wind-driven waves, although they behave in a similar manner. They are caused by elevation of the sea surface created by the lower atmospheric pressure at the center of the storm (**Chap. 7**).

Tsunamis consist of a series of waves with extremely long wavelengths (typically 100 to 200 km) and periods (typically 10 to 30 min). Only a very small fraction of the ocean is deeper than 6 km (**Fig. 4-4**), and half of the ocean floor is less than 4 km deep. Hence, the water depth is almost always less than one-twentieth of the tsunami’s wavelength, which causes tsunamis to behave as shallow-water waves. The speed of a shallow-water wave is determined by the water depth. In water 4 km deep, tsunamis travel at approximately $200 \text{ m}\cdot\text{s}^{-1}$ ($720 \text{ km}\cdot\text{h}^{-1}$), or nearly the speed of a jet airliner. Because tsunamis are shallow-water waves, their speed changes with depth (**Fig. 9-17**), and they are refracted as they pass over seafloor topography (**Fig. 9-24**). Tsunamis can be spread out or focused by undersea ridges or depressions, just as wind waves are as they approach a coastline.

When a tsunami travels over deep-ocean waters, its wave height rarely exceeds 1 or 2 m. Therefore, ships at sea are not affected by tsunamis. Indeed, it is almost impossible to detect a tsunami at sea because of its very long wavelength and limited wave height. A tsunami raises and lowers a ship only a meter or two, and each rise and fall takes several minutes. Tsunamis become dangerous only when they enter shallow water.

As a tsunami enters shallower water, it slows, and its wavelength is reduced, but its period is unchanged, as is true for any other wave (**Fig. 9-17**). As a wave slows, the wave height increases. Because water depth is very small in comparison to a tsunami’s wavelength, wave height builds very rapidly (**Fig. 9-19**). The tsunami does not break because its wavelength is so long that even a large increase in wave height does not produce steep, unstable waves. Nevertheless, the leading edge of the tsunami wave can produce tremendous surf as it flows turbulently across the shore and coast.

The tsunami reaches the shore as a wave that can be tens of meters high and can take 5 to 10 min to pass from trough to crest. As the tsunami moves inshore, sea level rises several meters

above normal, and enormous quantities of water are transported onshore and into any **estuaries** or rivers. The water keeps pouring onshore for several minutes as the wave crest approaches. The enormous energy stored in the wave is released as the water in the wave flows turbulently onto land and past any structures it encounters. Very strong currents and the equivalent of large breaking waves are generated as the water is concentrated in flows through harbors and channels and between structures. Buildings and trees can be destroyed, and boats and debris can be carried far inshore to be left stranded when the wave recedes (**Fig. 9-1**). If the ocean is not calm when the tsunami arrives, wind waves will add to the tsunami wave and may contribute to the destruction as they break far inland from the normal surf zone.

The impact that creates a tsunami may initially form either a trough or a crest. Accordingly, the first indication of the tsunami’s arrival at the coast may be a rise or recession in the normal sea surface level that lasts several minutes and exposes large areas of seafloor that are not normally exposed. Regardless of whether a trough or crest arrives at the coast first, the tsunami will consist of several waves following each other. After the first wave, successive waves may be larger, but they will eventually decrease in height. Waves can continue to arrive for 12 h or more. Many drownings occur when curious sightseers or beachcombers walk out onto a beach exposed by a tsunami trough and are caught by the following crest. Despite its 10- to 20-min period, the crest of a tsunami moves onshore much too fast for someone on the beach to escape after the water begins to rise.

In 1883, the Indonesian island volcano Krakatau erupted with an extremely violent explosion that almost instantly blew a large fraction of the island’s mass into the air. The explosion and the subsequent collapse of the remaining sides of the volcano into the underwater **caldera** (crater) created by the explosion caused a tsunami with waves of unusually long periods (estimated to be as much as 1 to 2 h). On the island of Java, about 60 km away from the eruption, the tsunami hit with waves about 30 m high. The waves destroyed many structures and carried a ship more than 3 km inland, where it was stranded almost 10 m above sea level. Krakatau’s tsunami killed an estimated 35,000 people and was observed by water-level recorders as far as 18,000 km away in Panama.

In 1946, an earthquake in the Aleutian Trench off Alaska caused a tsunami at Scotch Cap, Alaska, that destroyed a concrete lighthouse 10 m above sea level, killed the lighthouse operators, and tore down a nearby radio mast mounted 33 m above sea level. About 5 hours later, the tsunami heavily damaged the Hawaiian Islands and swept away 150 people to their deaths. In response to this type of disaster, a tsunami warning system was developed for the Pacific Ocean. As a result, when a tsunami hit Hawaii in 1957 with waves larger than those in 1946, no lives were lost.

On 26 December 2004, a great earthquake struck in the **subduction zone** just offshore from the Indian Ocean coastline of the northern part of the island of Sumatra in Indonesia. The earthquake generated a tsunami that was estimated to be 30 m high when it hit the coast of Sumatra. The tsunami spread across the Indian Ocean, smashing into Thailand to the east and India and Sri Lanka to the west. Continuing across the Indian Ocean to the west, the tsunami then impacted the western coastline of Africa. More than 220,000 people were killed or disappeared, with the majority of deaths occurring in Indonesia. Many deaths also

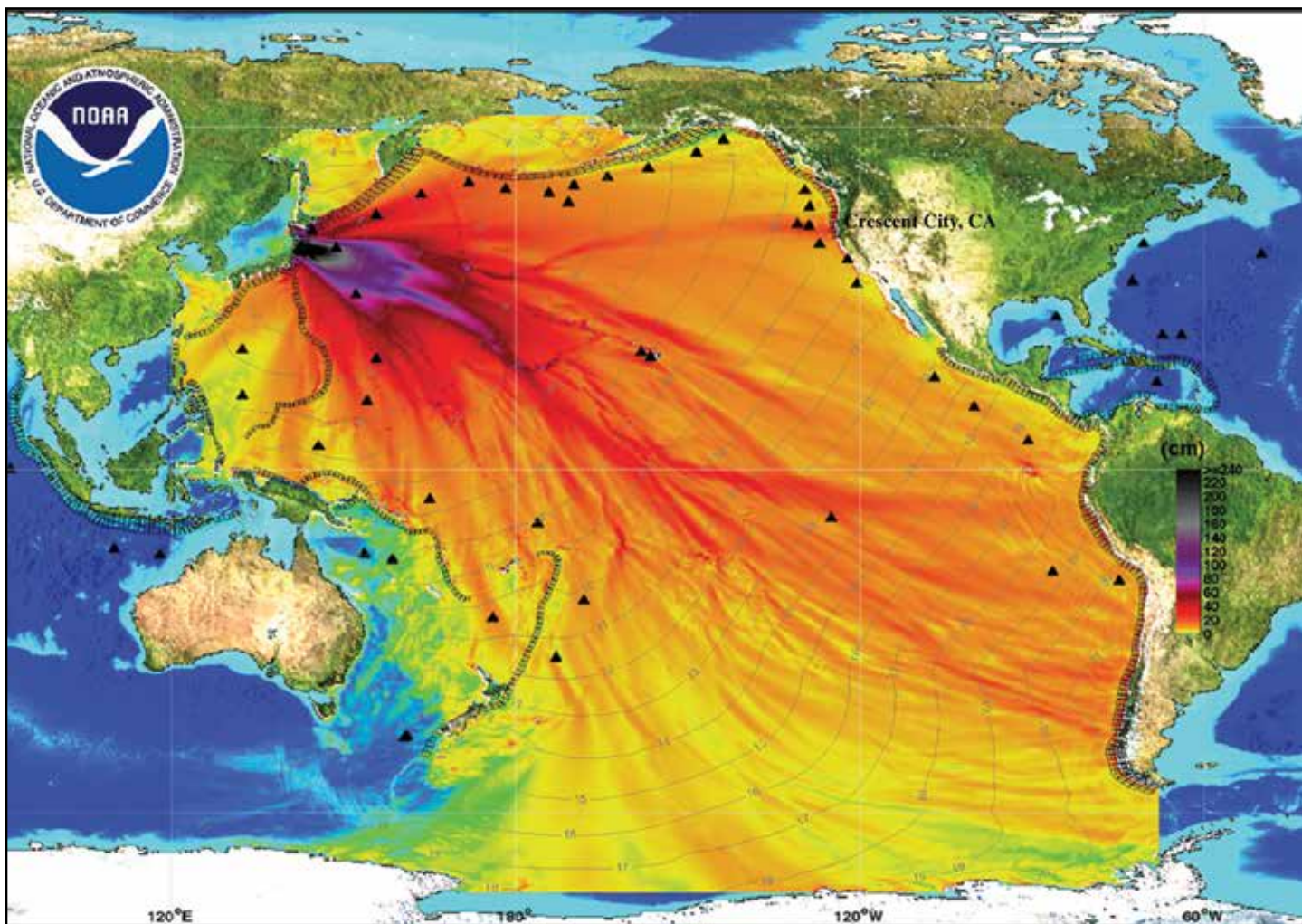


FIGURE 9-24. Computer model of the paths of the tsunami wave caused by the earthquake that occurred in 2011 offshore from Sendai, Japan. The wave energy of a tsunami is refracted by seafloor topography because tsunamis are shallow water waves. Refraction focuses or spreads the tsunami wave energy in the same way that wind wave energy is focused and spread at headlands and in bays. Note that one of the darker red streaks, which indicate paths along which the tsunami wave energy is focused, travels to Crescent City, California. Crescent City is extremely vulnerable to tsunamis, as are some Pacific Islands and locations along the South American Pacific Coast, due to this focusing effect.

occurred in Thailand, Sri Lanka, and India; and several deaths were even reported in Somalia, more than 5000 km from where the earthquake occurred. In addition to the deaths, hundreds of thousands were rendered homeless, and the damage to property is estimated to have been many billions of dollars. In March 2011, a tsunami approximately the same size as the 2004 Indonesian tsunami hit Japan. This tsunami caused massive destruction and took many lives, but not nearly as many died in 2011 as in 2004. Some of the credit for the smaller death toll is due to the tsunami detection and warning system built after the 2004 event, and some also undoubtedly belongs to the Japanese preparedness. Earthquake and tsunami awareness are a high priority in Japan, and frequent emergency drills to respond to such events are a routine part of Japanese schoolchildren's lives.

No doubt most of you who are reading this will have seen videos of the December 2004 or the March 2011 tsunami. Although some of the videos are horrific, they are also instructive. Many of the video records show that a tsunami does not arrive as a single short-lived wave. They also show that the often turbulent front edge of the advancing wave is followed by the mass of water in the wave continuing to pour ashore in a relentless current for several minutes before finally receding. Eyewitness accounts in both tsunamis also attest to the fact that several waves came ashore,

10 to 20 min apart, and that, in some places, the crest of the first wave arrived without warning, whereas in others, the trough arrived first, providing some warning as the ocean receded rapidly and much farther out than normal. The videos also show that it is not possible to outrun a tsunami wave unless one is lucky enough to be very close to the highest point the wave will reach. However, there were many survivors in each of these tsunamis. Some survivors saved themselves by running to higher ground at the first sign that a tsunami might hit, which was usually the shaking caused by the earthquake that generated the waves.

We should all learn from these events. It is imperative to seek higher ground immediately if we are on or near the shoreline and we either feel an earthquake or see the ocean rapidly recede in an abnormal fashion. We must also leave immediately if we see a massive wave moving toward shore, but unfortunately, fleeing might not guarantee safety. Finally, if a tsunami has occurred, even a small one, we must stay well away from the shore for at least 12 h.

Although the 2004 Indian Ocean and 2011 Japan tsunamis were events of epic human scale, they are both dwarfed by giant tsunamis that occurred before recorded history, and will probably occur again. For example, **Chapter 6** describes the monstrous tsunami that is thought to have been created when a meteorite

TABLE 9-2 Some Destructive Tsunamis since 1990

<i>Date</i>	<i>Location</i>	<i>Estimated Maximum Wave Height (m)</i>	<i>Number of Fatalities</i>
2 September 1992	Nicaragua	10	170
12 December 1992	Flores Island, Indonesia	26	>1000
12 July 1993	Okushiri, Japan	31	239
2 June 1994	East Java, Indonesia	14	238
14 November 1994	Mindoro Island, Philippines	7	49
9 October 1995	Jalisco, Mexico	11	1
1 January 1996	Sulawesi Island, Indonesia	3.4	9
17 February 1996	West Papua, Indonesia	7.7	161
21 February 1996	Northern coast of Peru	5	12
17 July 1998	Papua New Guinea	15	>2200
26 December 2004	Sumatra, Indonesia	30	>220,000
27 February 2010	Maule, Chile	8	ca.500
11 March 2011	Sendai, Honshu, Japan	47	>25,000
15 January 2022	Hunga Tonga Ha'apai, Tonga	20	6

hit the Earth at Chicxulub, Mexico. In addition, studies of the Hawaiian Islands have shown that huge tsunamis may be created when large segments of volcanic islands break loose and slump to the ocean floor (**Chap. 11**). A slump of 350 km³ of the island of Hawaii's coastline about 120,000 years ago led to the deposit of marine **fossils** in a location on the island that was at that time at least 5 km inland and at least 400 m above sea level. Blocks of **coral** have been found at a height of 325 m on the island of Lanai, perhaps swept upward by this same tsunami. The earliest historical record of a tsunami appears to be almost 4000 years old, when the Minoan city of Ugarit was documented on clay tablets as having been destroyed by giant waves, possibly created by a massive volcanic eruption far more powerful even than the eruption of Krakatau.

In 2022, the Hunga Tonga volcano eruption (**Chap. 4**) caused a tsunami 20 m high. Only 6 people died, a testament to the success of tsunami awareness education programs around the Pacific Ocean. However, this event was notable because it caused two different tsunamis, a traditional one caused by displacement of the water by the explosion, plus a type never observed before, a meteotsunami. This meteotsunami was caused by the intense atmospheric pressure (shock) wave from the volcanic explosion, which apparently pushed a tsunami ahead of it as it passed over the oceans. This meteotsunami travelled even faster than the ocean wave tsunami and arrived at Japan's coastline about two hours before the ocean wave tsunami.

Tsunamis are most common in the Pacific Ocean because it has many subduction zones, where earthquakes are likely to cause vertical seafloor movements. However, tsunamis may occur wherever vertical movements of the land or seafloor occur. Tsunamis are most likely to be damaging on island or continental coasts with narrow continental shelves because much of the wave energy can be dissipated as a tsunami moves over the shallow waters of a wide continental shelf. A tsunami may cause no damage at all on **atolls** or other islands that have no continental shelf, because the tsunami has no opportunity to build in height before

it reaches the coast. **Table 9-2** lists a number of destructive tsunamis that have occurred around the Pacific Ocean since 1990.

The tsunami warning system, headquartered in Hawaii, provides warnings of possible tsunamis whenever an earthquake occurs in the Pacific that might cause such waves. Often, tsunami warnings are not followed by a dangerous series of tsunami waves because the wave refraction patterns are complex and different for each tsunami. Therefore, even when a tsunami is actually observed near its source, predicting whether the tsunami will significantly affect any section of coast at a more remote location is very difficult. Even though some warnings may prove false, heeding such warnings is always wise.

In Hawaii and Oregon, tsunami warnings are broadcast through sirens at points along the coast and through the emergency radio and television broadcasting system. In the U.S. and some other nations, tsunami warnings are now broadcast on an emergency warning network. The US system is the Wireless Emergency System (WEA) that is active on all cell phones (but may be turned off, so make sure WEA is activated in your phone setting). If the tsunami is generated by a nearby earthquake the warning time will be very short so you should always leave the beach for higher ground immediately after you feel an earthquake. What feels like a "mild" earthquake may actually be a major earthquake centered some kilometers offshore, and a tsunami warning may be issued too late.

INTERNAL WAVES

Wind waves are oscillations that occur at the ocean surface where there is a sharp density discontinuity between water and the considerably less dense overlying atmosphere. Waves can be created at any density interface with a sharp density gradient where a fluid of low density overlies a fluid of higher density. Such sharp vertical density gradients, called pycnoclines, occur in the water column in many areas of the oceans (**Chap. 8**).

If a pycnocline is displaced up or down, the displacement will create internal waves that travel on the pycnocline. Relatively

little is known about internal waves, but their principal causes appear to be tidal motions, the effects of topography on currents moving in ocean water mass layers, and shear stress created between water layers as they flow across one another. Occasionally, where the pycnocline is shallow, internal waves can be generated by propellers or bow waves of ships.

The wave height of **internal waves** can be great (up to 100 m) in comparison with that of surface waves because a given amount of energy causes waves of larger amplitude where the density difference across the wave interface is smaller. The density difference across the pycnocline is much smaller than that across the sea surface. Internal waves travel approximately one-eighth as fast as surface waves with similar period, and they typically have periods of 5 to 8 min and wavelengths of 0.6 to 1 km. They have much less energy than surface waves, but they can be very important to sea life, submarines, offshore oil platforms, and vertical mixing of ocean waters.

Internal waves behave just like surface waves as they enter shallow water and interact with the seafloor. They slow, their wavelength is reduced, and eventually their wave height increases until they break. Because of their long wavelength, internal waves generally break on the outer part of the continental shelf. In some locations, including the continental shelf offshore of New York and New Jersey, breaking internal waves may mix **nutrient-rich**, cold water from below the pycnocline into warmer, nutrient-poor surface waters. This mechanism may supply nitrogen, phosphorus, and other nutrients to **phytoplankton** and thereby support larger populations of fishes and other animals than would otherwise be present (**Chaps. 12, 13**). Internal waves may also move **sediments** up and down canyons.

Submarines must be wary of internal waves because such waves can substantially change the submarine's depth in an uncontrollable and unpredictable way. Internal waves are speculated to have caused the sinking and loss of the nuclear-powered submarine USS Thresher, with its crew of 129, in 1963. Some types of drilling and oil production platforms can also be affected by internal waves. These are designed to withstand surface waves and are constructed on a tower resting on the seabed or on pontoons that float well below the depth of significant surface wave motion. In 1980, a series of internal waves rotated a production platform to face almost 90° from its original direction, although the platform did not topple.

Internal waves are generated not only on the main pycnocline but also at the interfaces between water mass layers and by interactions of the tide wave (**Chapter 10**) with seafloor topography. Thus, internal wave action occurs throughout the depths of the oceans and is a major contributor to vertical mixing that forms part of the MOC by returning deep-ocean water progressively to the surface layers.

ROSSBY AND KELVIN WAVES

Rossby waves, often called “planetary waves,” are caused by the interaction of the gradient in the magnitude of the Coriolis effect with latitude (**CC12**), and the **geostrophic** flow of water around a sea surface depression or with the flow of air around a depression or elevation of atmospheric pressure (**Chaps. 9, 10, CC13**). Thus, these waves occur both in the ocean and in the atmosphere. Their generation is a somewhat complex process, but in the ocean, they have wavelengths of hundreds to thousands of kilometers and wave heights of just a few centimeters. Because

they are so long and low, their presence in the oceans was not confirmed until satellites were able to measure sea surface height very precisely across wide areas of ocean within short periods of time.

Rossby waves move only from east to west. However, they can appear to move from west to east if they are carried by a much faster-moving air or water-mass movement. For example, satellite images show atmospheric Rossby waves as clouds following the large-scale **meanders** of the **jet stream**. Though weather systems generally move from west to east with the main flow of air masses in the atmosphere, Rossby waves embedded in this flow travel from east to west. Rossby waves move at speeds that vary with latitude, but the speeds of oceanic Rossby waves are on the order of only a few kilometers per day. Thus, for example, a single wave can take months or even years to cross the Pacific Ocean at mid latitudes.

There are two types of Kelvin waves: coastal and equatorial. Coastal Kelvin waves have sufficiently long periods and slow speeds that they are deflected into and constrained to move along a boundary by the Coriolis effect. Coastal Kelvin waves thus flow along the coastal margin in a counterclockwise direction in the Northern Hemisphere and a clockwise direction in the Southern Hemisphere. At the equator, where the Coriolis effect is zero, there is a special case where Kelvin waves flow directly along the equator from west to east. Equatorial Kelvin waves travel about three times as fast as Rossby waves, so they can cross the Pacific Ocean in about 70 days.

Rossby and Kelvin waves and their effects are poorly understood, but they are believed to affect phytoplankton distribution in the open oceans. They are also believed to affect weather—dramatically in some instances—by creating periodic but irregular variations in the location of ocean currents, such as the Gulf Stream, and in surface water temperatures (and thus atmospheric energy) in various ocean regions. Kelvin and Rossby waves are also associated with the development and relaxation of the El Niño/Southern Oscillation (**ENSO**; **Chap. 7**).

STANDING WAVES

Standing waves are completely different from the various types of progressive waves described previously in this chapter. Standing waves are sometimes called “stationary waves” or “seiches.” Their crests and troughs alternate at fixed locations, and they do not progress across the water surface.

A simple standing wave can be produced in a rectangular cake pan partially filled with water. If you slowly lift one end of the pan a few centimeters and then set it down quickly, the water will slosh back and forth from end to end of the pan. As you tilt the pan, the water surface remains level, but as you set it down, the water must move quickly so that the surface returns toward the level position. However, the surface overruns the level position, and water continues to flow until the surface is tilted in the direction opposite the tilt that occurred when you first set the pan down. An oscillating motion of the water surface continues back and forth (**Fig. 9-25a**) as the wave energy is reflected off either end of the pan until friction slows and finally stops the motion. The wavelength of the standing wave equals twice the length of the pan, and a standing wave is formed rather than progressive waves because the wave is blocked by (cannot progress past) the ends of the pan.

The water surface at the center of a standing wave does not

move up and down. This position is called a **node** (Fig. 9-25). At the **antinodes** (Fig. 9-25), which are at the ends of the standing wave, water within the waves can move only up and down; hence, there are no horizontal currents at these antinodes. Because water must be moved from one end of the wave to the other as it oscillates, water at the node moves back and forth horizontally. The current flows in one direction at the node as the wave moves in that direction, and then reverses when the wave moves

back. Horizontal or nearly horizontal reversing currents occur at all points within the wave, except at the antinodes. The maximum speed of these currents is highest at the node and decreases with distance from the node until it is zero at the antinodes.

Standing waves are important within lakes and restricted ocean basins. They form especially easily in basins with steep sides because the sides reflect wave energy and little energy is lost by friction with the seafloor. Standing waves are refracted

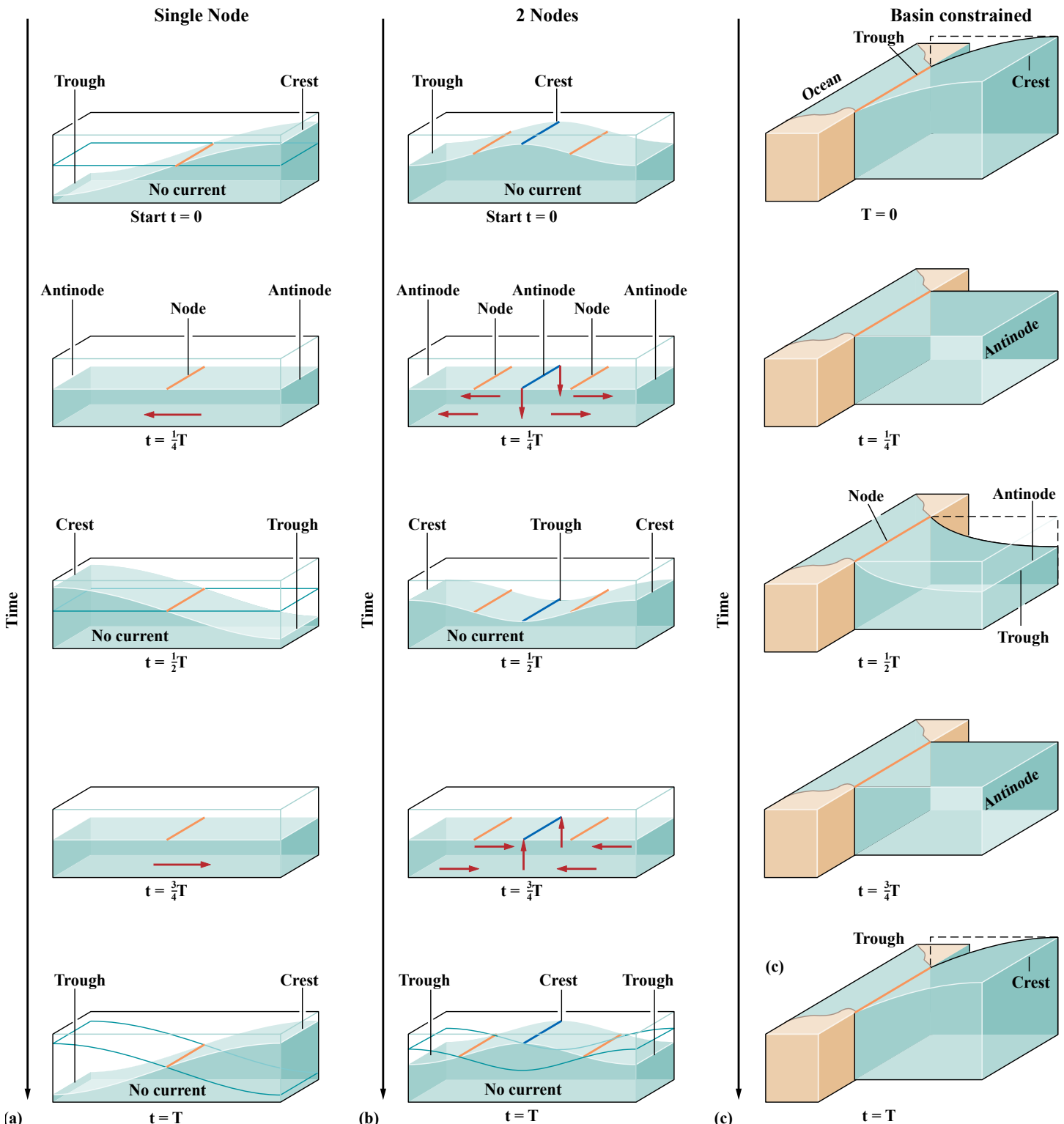


FIGURE 9-25. The motion of water in standing waves. The standing-wave motion is a seesaw oscillation of the surface. Standing waves have one or more nodes (where there is no change in the water surface height but there are oscillating horizontal currents) and one or more antinodes (where there are no currents but the surface oscillates up and down). (a) A standing wave with a single node. (b) A standing wave with two nodes. (c) A standing wave that is essentially a half wave with a node at the basin entrance and only one antinode, at the closed end of the basin.

like progressive waves. Because water moves horizontally except at the antinodes, standing waves in very large basins, such as the Great Lakes of North America, are deflected by the Coriolis effect. The influence of the Coriolis effect on a standing tide wave is examined in **Chapter 10**.

The standing wave just described is essentially one-half of a wave because the crest and trough of the wave are at opposite ends of the basin. Standing waves with more than one node can be established in certain basins (**Fig. 9-25b**).

When a progressive wave of exactly the right period arrives at the entrance to a basin of exactly the correct length, a standing wave is established in the basin. Each successive crest of the standing wave must arrive at the basin entrance at the same time that a crest of a progressive wave arrives from the other direction. This type of **tuned** oscillation is often important in tidal motions within enclosed bays or estuaries (**Chap. 10**). The oscillation is tuned in much the same way that organ pipes are tuned to specific wavelengths of air oscillations that create different musical notes. The pure note in an organ pipe is a single-node standing wave, whereas harmonics are standing waves that have two or more nodes within the pipe.

CHAPTER SUMMARY

Complexity of Ocean Waves.

Waves usually seem to come in haphazard sequences of heights and periods. The reason is wave interference, the combination of waves of several different periods and from different directions.

Wave Motion.

Water within a progressive wave moves in almost circular orbits whose diameters decrease with depth and are almost zero at a depth of half the wavelength. There is a very small net forward motion of water with the wave. Waves are created when the water surface is displaced. Once started, the wave motion is sustained by a restoring force that tends to return the sea surface to a flat, level state. Gravity is the principal restoring force for most ocean waves, and surface tension is important for very short-period capillary waves. The Coriolis effect affects very long wavelength waves, such as tides and tsunamis.

Tides are created by gravitational attractions of the sun and moon. Some ocean waves are caused by earthquakes or the passage of vessels. Most ocean waves are created by winds. Winds blowing over a calm water surface create tiny capillary waves that increase sea surface roughness. The wind increases the wave height and causes capillary waves to be combined into waves with longer wavelengths.

Capillary waves are dissipated quickly as energy is lost through water viscosity. Most ocean waves are gravity waves and lose little energy until they reach the shore, break, and dissipate much of their energy as heat.

Wave Breaking and Wave Height.

Winds are usually variable, causing seas with waves of many different wavelengths and heights. If winds are strong and blow long enough, waves begin to break when their height is one-seventh of their wavelength. Maximum wave heights are determined by the wind strength and duration and by the fetch. Wave heights up to 34 m or more have been reported. Wave period and wave steepness increase when waves travel directly into a current.

Wave Trains and Wave Dispersion.

Progressive waves travel in groups called “trains” that move at half the speed of the individual waves. The leading wave in the train is continuously destroyed and a new one created at the rear. Wave trains having waves of different wavelengths combine to produce the confused sea state that is characteristic of storms. The speed of deep-water waves increases with wavelength, so waves of different wavelengths move away from a storm at different speeds. Thus, waves are sorted by wavelength dispersion as they move away from a storm. As wavelength dispersion occurs, wave steepness declines and a swell is formed.

Waves in Shallow Water.

When waves enter water shallower than half their wavelength, the water’s orbital motion encounters the seafloor. As a result, wave orbits are flattened and both wave speed and wavelength are reduced, while period remains unchanged. Waves continue to slow as they enter progressively shallower water until the water depth is less than one-twentieth of the wavelength, after which the speed is determined only by depth. Waves are refracted in shallow water because any part of the wave in shallower water is slowed more than any part in deeper water. Refraction tends to turn waves to align parallel to the shore, focuses wave energy on headlands, and spreads energy within bays. Waves are reflected off barriers such as seawalls, and they are diffracted when part of the wave passes a barrier that blocks the rest of the wave.

As waves enter shallow water, wave height slowly decreases until water depth is about one-tenth of the wavelength and then increases rapidly as depth decreases further. Waves break when they become oversteep. There are four types of breakers: spilling breakers, in which the crest tumbles down the front of the wave; plunging breakers, in which the crest outruns the bottom of the wave and curls over before crashing down; collapsing breakers, in which the front face of the wave collapses; and surging breakers, in which the water simply surges up and down the shoreface.

Waves transport water forward onto the beach. Water returns offshore through narrow rip currents at intervals along the beach. Rip currents are a major cause of drownings, but even weak swimmers can survive them if they are aware that rip currents are narrow.

Tsunamis and Storm Surges.

Tsunamis are trains of very long-wavelength (100 to 200 km) waves with periods of 10 to 30 min created by earthquakes or other such events that abruptly displace a section of seafloor. Tsunamis travel at speeds in excess of $700 \text{ km} \cdot \text{h}^{-1}$ but behave as shallow-water waves because their wavelength far exceeds the ocean depths. Tsunamis are rarely more than a meter or two in height until they enter shallow coastal waters, where their height builds rapidly. Tsunamis can do tremendous damage because they pour onshore for 10 min or more before the wave crest passes.

Hurricanes and other major storms can cause storm surges in which the water level ahead of the storm is elevated. Storm surge can reach far inland of the normal high water line.

Rossby and Kelvin Waves.

Rossby waves are very low-amplitude waves that move slowly from east to west, have wavelengths of tens or hundreds of kilometers, and are responsible for periodic but irregular variations in weather along their track. Kelvin waves flow along the coastlines of the ocean basins—counterclockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere, and directly west to east at the equator.

Internal Waves.

Internal waves form on pycnoclines. They have long periods and wavelengths, have large heights in comparison with surface waves, and tend to break near the edges of continental shelves, where they enhance the vertical mixing of water.

Standing Waves.

Standing waves are formed in basins where the ends of the basin prevent progressive waves from passing. At the node of a standing wave, the water surface does not move vertically but there are horizontal reversing currents. At the antinodes, water motion is vertical and there are no horizontal currents

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.

amplitude	progressive waves
atolls	pycnoclines
beach	reef
caldera	refracted
capillary waves	rip currents
climate	scuba
coastlines	sea
continental shelf	seawalls
coral reef	sediments
coral reef	shallow-water waves
Coriolis effect	shear stress (friction)
crest	shore
current	shoreline
deep-water wave	slumps
density	standing wave
ENSO	storm surge
erode	subduction zone
estuaries	surf
extratropical cyclones	surf zone
fetch	surface tension
fossils	swell
frequency	tide
fringing reefs	topography
geostrophic	trade winds
gravity waves	trough
greenhouse effect	tsunamis
hurricane	turbidity currents
intermediate waves	turbulent
internal waves	wave dispersion
jet stream	wave heights
joules	wave interference
kinetic energy	wave period
leeward	wave rays
longshore bar	wave speed
longshore currents	wave steepness
meanders	wavelength
nutrient	westerly
phytoplankton	windward
potential energy	

STUDY QUESTIONS

1. Why do successive waves that arrive at the beach have different heights?
2. You are standing at the end of a pier with a stopwatch. How would you measure the average wavelength of the waves passing by?
3. What is a restoring force, and why is it necessary if waves are to develop?
4. List the factors that determine the maximum wave height in a sea. How do they differ in the Atlantic and Pacific Oceans?
5. Why do deep-water waves sometimes break instead of just getting bigger?
6. Why is it not a good idea to enter a narrow harbor mouth when the tide is flowing out of the entrance and large waves are entering the harbor mouth from offshore?
7. Why do waves disperse as they move out from a storm? What would you see if you stood at the beach and observed the waves for many hours after the first waves from a distant storm arrived on an otherwise calm sea?
8. What are wave trains? Why do they move more slowly than individual waves?
9. What are the principal differences between internal waves and surface waves? Why do these differences exist?
10. What are rip currents, and why do they occur?
11. Why do tsunamis travel almost as fast as jet aircraft? Why would you not even notice a passing tsunami if you were on a boat far out to sea in deep water?
12. Describe standing waves. How do they differ from progressive waves? How do they resemble progressive waves?

CRITICAL THINKING QUESTIONS

1. If the surface tension of water were much smaller than it is, how would you expect this to affect the formation of waves on the ocean? How would the waves behave differently when they approached a beach?
2. You are sailing across the water into an almost regular swell that comes from directly ahead of you. Suddenly you notice that the same swell now appears to be coming at you from two slightly different directions at a small angle from each side of the boat's bow and the wave pattern ahead looks confused compared to the smooth swell you were sailing on a few minutes before. What are you seeing, and why? Should you be concerned?
3. Sailing ships exploring the oceans before there were maps were able to safely enter lagoons of atolls or those behind fringing coral reefs, even though in many such reefs there are only a few narrow entrances where the water is deep enough for safe passage. (a) How did they do this? (b) How might they have done this differently on days when the ocean surface was extremely calm, lacking even a gentle swell?
4. Describe how waves would be refracted if they entered a very long basin whose underwater sides described a perfect V shape, with the depth of the V slowly decreasing with distance into the basin. Draw your answer showing the shapes of several successive waves as they travel up the basin. Include wave rays in your diagram.
5. In some parts of the oceans, there are often strong seas with breaking waves. In other areas, the waves are usually smooth swells. In yet other areas, the sea surface is often calm, and finally, in some areas, ships may encounter large swell waves with steepened fronts. Using what you have learned in this

- chapter, identify on a map at least one area of the Pacific Ocean where you would expect to find each of these situations. Explain the reasons for your choices.
6. In strong storms at sea, ships often alter course, for safety, so that they travel directly into the direction from which the wind and waves are coming, even though this may be far from their intended course of travel. Why do you think it is safer to travel into the wind and seas than at an angle across this direction?
 7. In extreme storms, ships may turn and travel in the same direction as the wind and waves are traveling, even if doing so takes them in almost the opposite direction from their intended course. Why do you think this might be safer than traveling into the wind and waves?
 8. Are there internal waves in the atmosphere? If so, where would you be most likely to find them? If there were internal waves in the atmosphere, would you expect their wavelengths to be longer or shorter than those of internal waves in the oceans? Why?

CRITICAL CONCEPTS REMINDERS

CC5 Transfer and Storage of Heat by Water: Water's high heat capacity allows large amounts of heat to be stored in the oceans with little change in temperature. Thus, when waves break and release their energy as heat, they cause very little change in the temperature of the water.

CC9 The Global Greenhouse Effect: Major climate and climate related changes may be an inevitable result of our burning fossil fuels. The burning of fossil fuels releases carbon dioxide and other gases into the atmosphere, where they accumulate and act like the glass of a greenhouse retaining more of the sun's heat. One of these climate related changes is the possibility that average wave heights in the oceans will increase, which would add to existing safety issues for ocean vessels and increase shoreline erosion rates.

CC12 The Coriolis Effect: Water masses move freely over the Earth surface while the solid Earth itself is constrained to move with the Earth's rotation. This causes moving water masses, including some long period waves, to appear to follow curving paths across the Earth's surface. The apparent deflection, called the Coriolis effect, is to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. It is at a maximum at the poles, reduces at lower latitudes, and becomes zero at the equator

CC13 Geostrophic Flow: Water and air masses flowing on horizontal pressure gradients are deflected by the Coriolis effect until they flow across the gradient such that the pressure gradient force and Coriolis effect are balanced, a condition called geostrophic flow. The interaction of geostrophic currents and the change of the magnitude of the Coriolis effect with latitude are the cause of Rossby waves that flow east to west across the oceans and atmosphere. The meanders in the jet stream seen in many weather maps are Rossby waves.

REFERENCES

Figure 9-1 – Welch, G., 2011: A large ferry boat rests inland amidst destroyed houses, ID 110320-M-0145H-063. United States Navy, accessed 26 June 2025, [https://commons.wikimedia.org/wiki/File:US_Navy_110320-M-0145H-063_A_large_ferry_boat_rests_inland_amidst_destroyed_houses_after_a_9.0_earthquake_and_subsequent_tsunami_struck](https://commons.wikimedia.org/wiki/File:US_Navy_110320-M-0145H-063_A_large_ferry_boat_rests_inland_amidst_destroyed_houses_after_a_9.0_earthquake_and_subsequent_tsunami_struck_Japan_March.jpg)

[Japan_March.jpg](#).

Figure 9-5 – Adapted from Kinsman, B., 1965: *Wind Waves, their generation and propagation on the ocean surface*. Prentice Hall, 676 pp.

Figure 9-7d – Adapted from Sverdrup, H. U., M. W. Johnson, and R. H. Fleming, 1942: *The Oceans: their physics, chemistry, and general biology*. Prentice Hall, 1087.

Figure 9-8c – Kharif, C., E. Pelinovsky, and A. Slunyaev, 2009: Observation of Rogue Waves, *Rogue Waves in the Ocean*. Springer, Berlin, Heidelberg, 11–31. https://doi.org/10.1007/978-3-540-88419-4_2.

Figure 9-12 – Arpingstone, 2004: Two boat wake, Avon Gorge. Accessed 9 December 2025, <https://commons.wikimedia.org/wiki/File:Wake.avon.gorge.2boats.arp.750pix.jpg>.

Figure 9-17 – Thurman, H. V., 1988: *Introductory oceanography 5th Edition*. Charles E. Merrill, 515 pp.

Figure 9-21 – Segar, D., and E. Stamman Segar, 1997: Surfer riding a tube, Oahu, Hawaii.

Figure 9-23b,c – NWS, 2012: Rip current science. Accessed 6 January 2026, <https://www.weather.gov/safety/ripcurrent-science>.

Figure 9-24 – NTCR PMEL, 2011: Energy of tsunami of The Honshu, Japan tsunami of 11 March 2011. NOAA, accessed 27 June 2025, https://commons.wikimedia.org/wiki/File:Energy_plot20110311-1000.png.