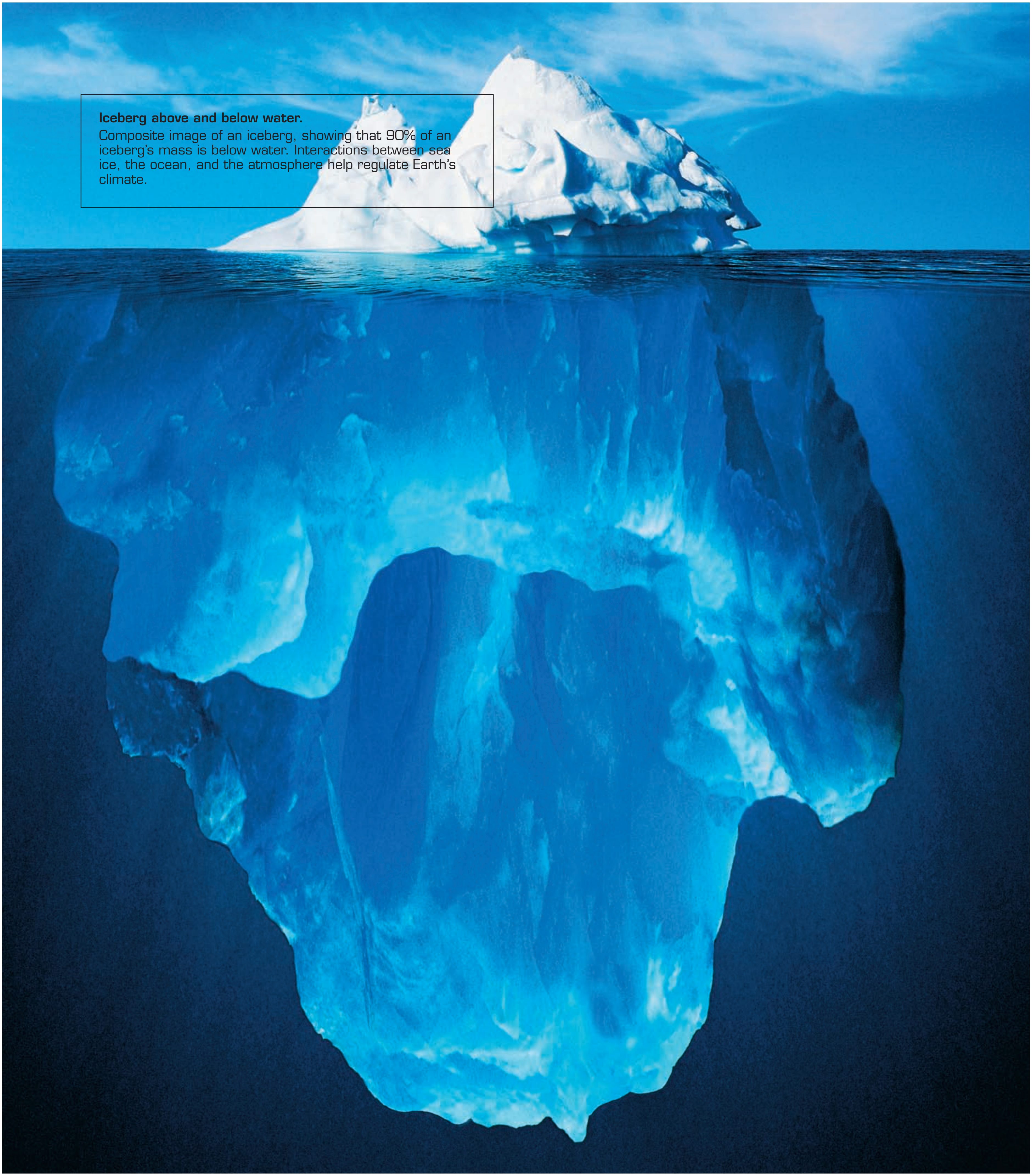

Iceberg above and below water.
Composite image of an iceberg, showing that 90% of an iceberg's mass is below water. Interactions between sea ice, the ocean, and the atmosphere help regulate Earth's climate.

"When the still sea conspires an armor
And her sullen and aborted
Currents breed tiny monsters,
True sailing is dead
Awkward instant
And the first animal is jettisoned . . ."

—The Doors,
Horse Latitudes (1972)

6

AIR–SEA INTERACTION

CHAPTER AT A GLANCE

- Earth's seasons are caused by the tilt of Earth's axis, which always points in the same direction and thus alternately tips each hemisphere more toward the Sun during its respective summer.
- Each hemisphere has three major wind belts, in order from the equator to the pole: the trade winds, the prevailing westerlies, and the polar easterlies.
- Hurricanes (also called cyclones or typhoons) are powerful and sometimes destructive tropical storms that form in high-temperature waters and are influenced by the Coriolis effect and Earth's wind belts.

One of the most remarkable things about our planet is that the atmosphere and the ocean act as one interdependent system. Observations of the atmosphere–ocean system show that what happens in one causes changes in the other. Further, the two parts of this system are linked by complex feedback loops, some of which reinforce a change and others that nullify any changes. Surface currents in the oceans, for instance, are a direct result of Earth's atmospheric wind belts. Conversely, certain atmospheric weather phenomena are manifested in the oceans. In order to understand the behavior of the atmosphere and the oceans, their mutual interactions and relationships must be examined.

Solar energy heats the surface of Earth and creates atmospheric winds, which, in turn, drive most of the surface currents and waves in the ocean. Radiant energy from the Sun, therefore, is responsible for motion in the atmosphere and the ocean. Recall from Chapter 5 that the atmosphere and ocean use the high heat capacity of water to constantly exchange this energy, shaping Earth's global weather patterns in the process.

Periodic extremes of atmospheric weather, such as droughts and profuse precipitation, are related to periodic changes in oceanic conditions. For instance, it was recognized as far back as the 1920s that El Niño—an ocean event—was tied to catastrophic weather events worldwide. What is as yet unclear, however, is if changes in the ocean produce changes in the atmosphere that lead to El Niño conditions—or vice versa. El Niño–Southern Oscillation events are discussed in Chapter 7, "Ocean Circulation."

Air–sea interactions have important implications in global warming, too. A multitude of recent studies have confirmed that the atmosphere is experiencing unprecedented warming as a result of human-caused emissions of carbon dioxide and other gases that absorb and trap heat in the atmosphere. This atmospheric heat is being transferred to the oceans and has the potential to cause widespread marine ecosystem changes. This issue is discussed in Chapter 16, "The Oceans and Climate Change."

In this chapter, we'll examine the redistribution of solar heat by the atmosphere and its influence on oceanic conditions. First, large-scale phenomena that influence air–sea interactions are studied, and then smaller scale phenomena are examined.

6.1 What Causes Earth's Seasons?

Earth revolves around the Sun along an elliptical path (Figure 6.1). The plane traced by Earth's orbit is called the **ecliptic**. Earth's axis of rotation is not perpendicular ("upright") on the ecliptic; rather, it tilts at an angle of 23.5 degrees. Figure 6.1 shows that throughout the yearly cycle, Earth's axis *always points in the same direction*, which is toward Polaris, the North Star.

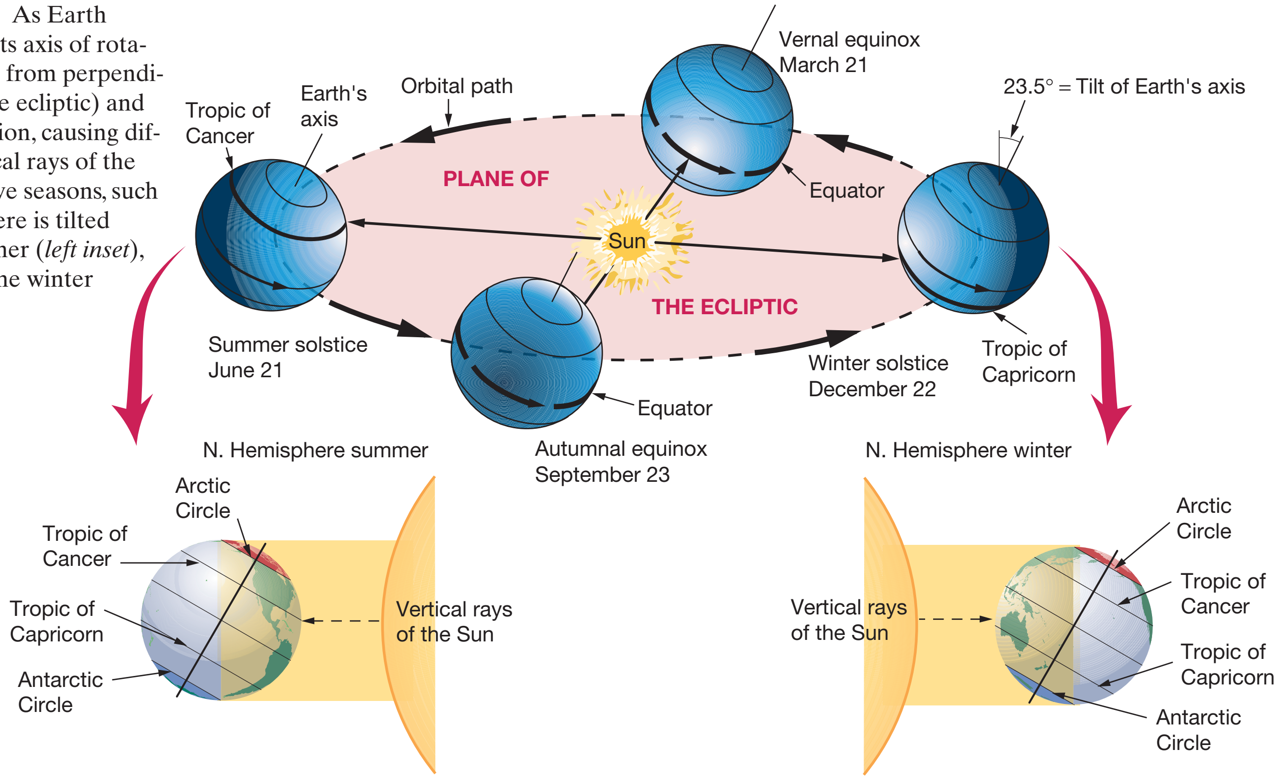

FIGURE 6.1 Earth's seasons. As Earth orbits the Sun during one year, its axis of rotation constantly tilts 23.5 degrees from perpendicular (relative to the plane of the ecliptic) and always points in the same direction, causing different areas to experience vertical rays of the Sun. This tilt causes Earth to have seasons, such as when the Northern Hemisphere is tilted toward the Sun during the summer (*left inset*), and away from the Sun during the winter (*right inset*).

web animation
Earth-Sun Relations

The tilt of Earth's rotational axis (and not its elliptical path) causes Earth to have seasons. Spring, summer, fall, and winter occur as follows:

- At the **vernal equinox** (*vernus* = spring; *equi* = equal, *noct* = night), which occurs on or about March 21, the Sun is directly overhead along the equator. During this time, all places in the world experience equal lengths of night and day (hence the name *equinox*). In the Northern Hemisphere, the vernal equinox is also known as the spring equinox.
- At the **summer solstice** (*sol* = the Sun, *stitium* = a stoppage), which occurs on or about June 21, the Sun reaches its most northerly point in the sky, directly overhead along the **Tropic of Cancer**, at 23.5 degrees north latitude (Figure 6.1, *left inset*). To an observer on Earth, the noonday Sun reaches its northernmost or southernmost position in the sky at this time and appears to pause—hence the term *solstice*—before beginning its next six-month cycle.
- At the **autumnal** (*autumnus* = fall) **equinox**, which occurs on or about September 23, the Sun is directly overhead along the equator again. In the Northern Hemisphere, the autumnal equinox is also known as the fall equinox.
- At the **winter solstice**, which occurs on or about December 22, the Sun is directly overhead along the **Tropic of Capricorn**, at 23.5 degrees south latitude (Figure 6.1, *right inset*). In the Southern Hemisphere, the seasons are reversed. Thus, the winter solstice is the time when the Southern Hemisphere is most directly facing the Sun, which is the beginning of the Southern Hemisphere summer.

Because Earth's rotational axis is tilted 23.5 degrees, the Sun's **declination** (angular distance from the equatorial plane) varies between 23.5 degrees north and 23.5 degrees south of the equator on a yearly cycle. As a result, the region between these two latitudes (called the **tropics**) receives much greater annual radiation than polar areas.

Seasonal changes in the angle of the Sun and the length of day profoundly influence Earth's climate. In the Northern Hemisphere, for example, the longest day occurs on the summer solstice and the shortest day on the winter solstice.

Daily heating of Earth also influences climate in most locations. Exceptions to this pattern occur north of the **Arctic Circle** (66.5 degrees north latitude) and south of the **Antarctic Circle** (66.5 degrees south latitude), which at certain times of the year do not experience daily cycles of daylight and darkness. For instance, during the Northern Hemisphere winter, the area north of the Arctic Circle receives no direct solar radiation at all and experiences up to six months of darkness. At the same time, the area south of the Antarctic Circle receives continuous radiation ("midnight Sun"), so it experiences up to six months of light. Half a year later, during the Northern Hemisphere summer (the Southern Hemisphere winter), the situation is reversed.

KEY CONCEPT

Earth's axis is tilted at an angle of 23.5 degrees, which causes the Northern and Southern Hemispheres to take turns "leaning toward" the Sun every six months and results in the change of seasons.

6.2 How Does Uneven Solar Heating Affect Earth?

The side of Earth facing the Sun (the daytime side) receives a tremendous dose of intense solar energy. This energy drives the global ocean–atmosphere engine, creating pressure and density differences that stir currents and waves in both the atmosphere and the ocean.

Distribution of Solar Energy

If Earth were a flat plate in space, with its flat side directly facing the Sun, sunlight would fall equally on all parts of Earth. Earth is spherical, however, so the amount and intensity of solar radiation received at higher latitudes are much less than at lower latitudes. The following factors influence the amount of radiation received at low and high latitudes:

- Sunlight strikes low latitudes at a high angle, so the radiation is concentrated in a relatively small area (area *A* in Figure 6.2). Sunlight strikes high latitudes at a low angle, so the same amount of radiation is spread over a larger area (area *B* in Figure 6.2).
- Earth's atmosphere absorbs some radiation, so less radiation strikes Earth at high latitudes than at low latitudes, because sunlight passes through more of the atmosphere at high latitudes.
- The **albedo** (*albus* = white) of various Earth materials is the percentage of incident radiation that is reflected back to space. The average albedo of Earth's surface is about 30%. More radiation is reflected back to space at high latitudes because ice has a much higher albedo than soil or vegetation.
- The angle at which sunlight strikes the ocean surface determines how much is absorbed and how much is reflected. If the Sun shines down on a smooth sea from directly overhead, only 2% of the radiation is reflected, but if the Sun is only 5 degrees above the horizon, 40% is reflected back into the atmosphere (Table 6.1). Thus, the ocean reflects more radiation at high latitudes than at low latitudes.

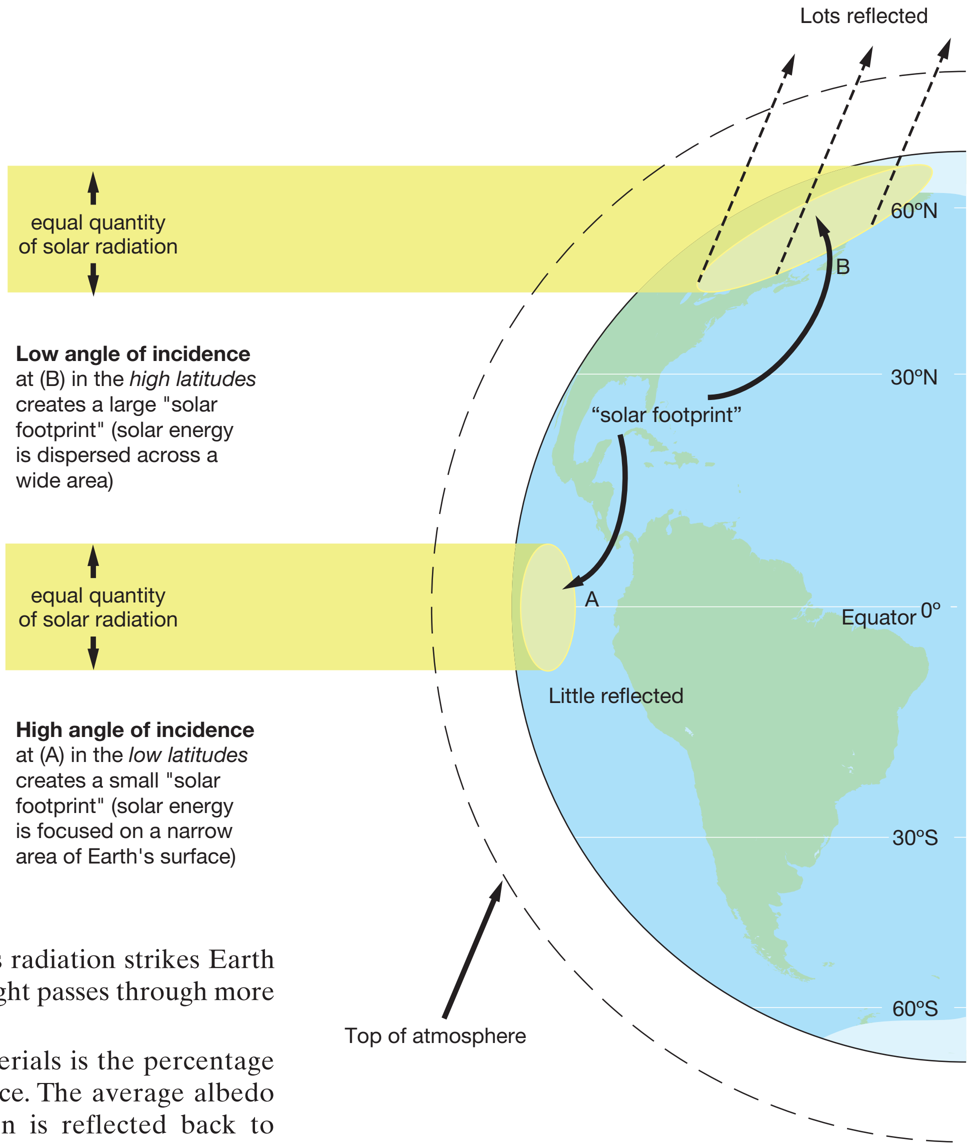

FIGURE 6.2 Solar radiation received on Earth. Two identical beams of sunlight strike Earth. At *A*, the light beam is focused on a narrow area of Earth's surface and produces a smaller "solar footprint"; at *B*, the light beam is dispersed across a wide area and produces a larger "solar footprint." Additionally, more light is reflected at *B*. Thus, the amount of solar energy received at higher latitudes is much less than that at lower latitudes.

TABLE 6.1 REFLECTION AND ABSORPTION OF SOLAR ENERGY RELATIVE TO THE ANGLE OF INCIDENCE ON A FLAT SEA

Elevation of the Sun above the horizon	90°	60°	30°	15°	5°
Reflected radiation (%)	2	3	6	20	40
Absorbed radiation (%)	98	97	94	80	60

Because of all these reasons, the intensity of radiation at high latitudes is greatly decreased compared with that falling in the equatorial region.

Other factors influence the amount of solar energy that reaches Earth. For example, the amount of radiation received at Earth's surface varies *daily* because Earth rotates on its axis so the surface experiences daylight and darkness each day. In addition, the amount of radiation varies *annually* due to Earth's seasons, as discussed in the previous section.

Oceanic Heat Flow

Close to the poles, much incoming solar radiation strikes Earth's surface at low angles. Combined with the high albedo of ice, more energy is reflected back into space than absorbed. In contrast, between about 35 degrees north latitude and 40 degrees south latitude,[1] sunlight strikes Earth at much higher angles and more energy is absorbed than reflected back into space. The graph in Figure 6.3 shows how incoming sunlight and outgoing heat combine on a daily basis for a net heat gain in low-latitude oceans and a net heat loss in high-latitude oceans.

Based on Figure 6.3, you might expect the equatorial zone to grow progressively warmer and the polar regions to grow progressively cooler. The polar regions are always considerably colder than the equatorial zone, but the temperature *difference* remains the same because excess heat is transferred from the equatorial zone to the poles. How is this accomplished? Circulation in both the oceans and the atmosphere transfers the heat.

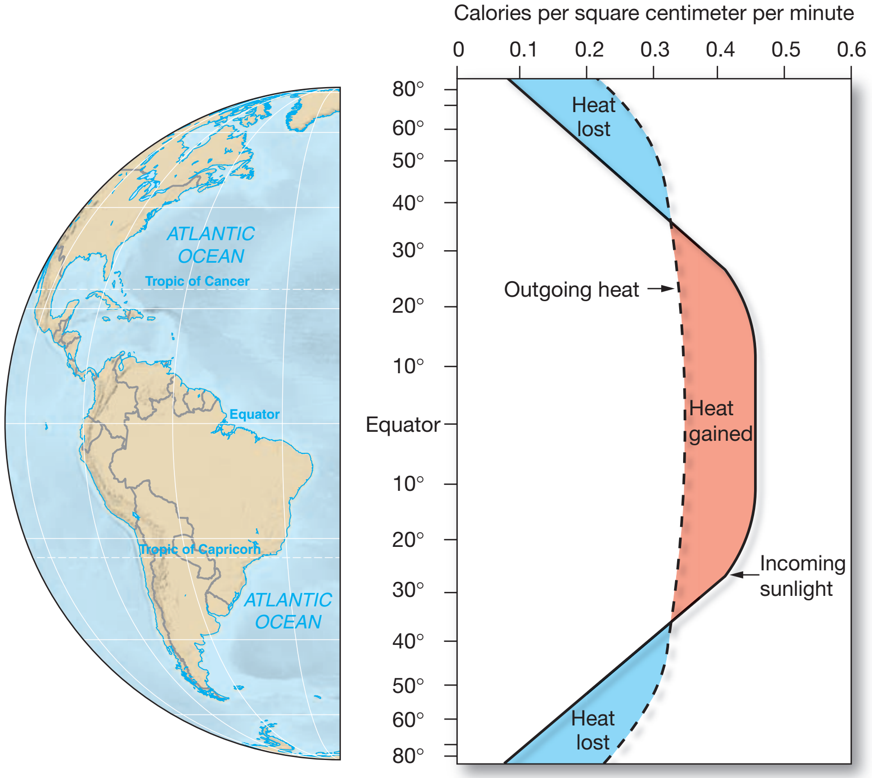

FIGURE 6.3 Heat gained and lost from the ocean varies with latitude. Heat gained by the oceans in equatorial latitudes (*red portion of graph*) equals heat lost in polar latitudes (*blue portion of graph*). On average, the two balance each other, and the excess heat from equatorial latitudes is transferred to heat-deficient polar latitudes by both oceanic and atmospheric circulation.

6.3 What Physical Properties Does the Atmosphere Possess?

The atmosphere transfers heat and water vapor from place to place on Earth. Within the atmosphere, complex relationships exist among air composition, temperature, density, water vapor content, and pressure. Before we apply these relationships, let's examine the atmosphere's composition and some of its physical properties.

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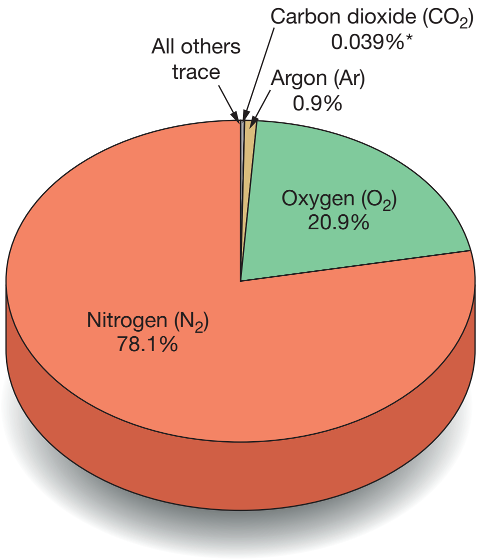
[1] Note that this latitudinal range extends farther into the Southern Hemisphere because the Southern Hemisphere has more ocean surface area in the middle latitudes than the Northern Hemisphere does.

Composition of the Atmosphere

Figure 6.4 lists the composition of dry air and shows that the atmosphere consists almost entirely of nitrogen and oxygen. Other gases include argon (an inert gas), carbon dioxide, and others in trace amounts. Although these gases are present in very small amounts, they can trap significant amounts of heat within the atmosphere. For more about how these gases trap heat in the atmosphere, see Chapter 16, "The Oceans and Climate Change."



*Note that the concentration of carbon dioxide in the atmosphere is increasing by 0.5% per year due to human activities

FIGURE 6.4 Composition of dry air. Pie chart showing the composition of dry air (without any water vapor). Nitrogen and oxygen gas comprise 99% of the total, with several trace gases making up the rest; the most significant trace gas is carbon dioxide, an important greenhouse gas.

Temperature Variation in the Atmosphere

Intuitively, it seems logical that the higher one goes in the atmosphere, the warmer it should be since it's closer to the Sun. However, as unusual as it seems, the atmosphere is actually heated from *below*. Moreover, the Sun's energy passes through the Earth's atmosphere and heats the Earth's surface (both land and water), which then reradiates this energy as heat into the atmosphere. This process is known as the *greenhouse effect* and will be discussed in more detail in Chapter 16, "The Oceans and Climate Change."

Figure 6.5 shows a temperature profile of the atmosphere. The lowermost portion of the atmosphere, which extends from the surface to about 12 kilometers (7 miles), is called the **troposphere** (*tropo* = turn, *sphere* = a ball) and is where all weather is produced. The troposphere gets its name because of the abundance of mixing that occurs within this layer of the atmosphere, mostly as a result of being heated from below. Within the troposphere, temperature gets cooler with altitude to the point that at high altitudes, the air temperature is well below freezing. If you have ever flown in a jet airplane, for instance, you may have noticed that any water on the wings or inside your window freezes during a high-altitude flight.

Density Variation in the Atmosphere

It may seem surprising that air has density, but since air is composed of molecules, it certainly does. Temperature has a dramatic effect on the density of air. At higher temperatures, for example, air molecules move more quickly, take up more space, and density is decreased. Thus, the general relationship between density and temperature is as follows:

- Warm air is less dense, so it rises; this is commonly expressed as "heat rises."
- Cool air is more dense, so it sinks.

Figure 6.6 shows how a radiator (heater) uses convection to heat a room. The heater warms the nearby air and causes it to expand. This expansion makes the air less dense, causing it to rise. Conversely, a cold window cools the nearby air and causes it to contract, thereby becoming more dense, which causes it to sink. A **convection** (*con* = with, *vect* = carried) **cell** forms, composed of the rising and sinking air moving in a circular fashion, similar to the convection in Earth's mantle discussed in Chapter 2.

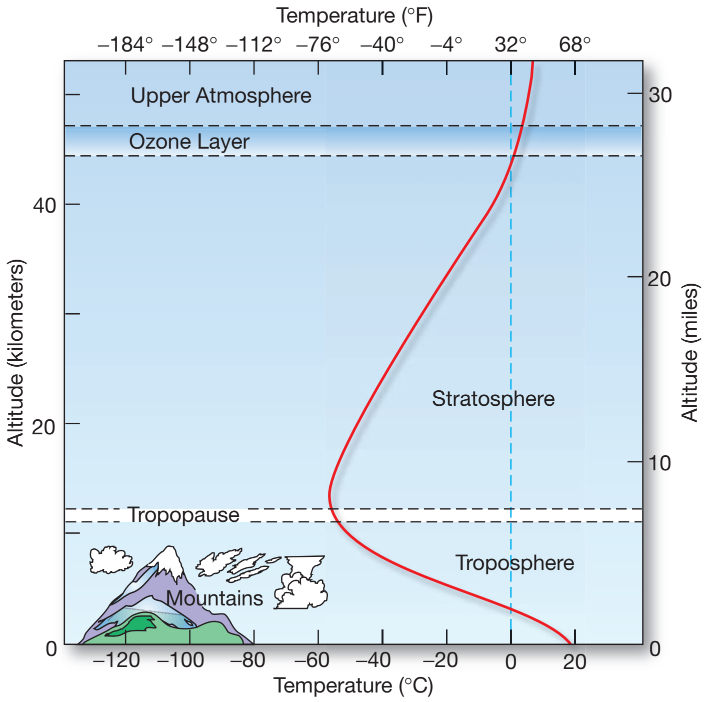


FIGURE 6.5 Temperature profile of the atmosphere. Within the troposphere, the atmosphere gets cooler with increasing altitude. Above the troposphere, the atmosphere generally warms.

Atmospheric Water Vapor Content

The amount of water vapor in air depends in part on the air's temperature. Warm air, for instance, can hold more water vapor than cold air because the air molecules are moving more quickly and come into contact with more water vapor. Thus, warm air is typically moist, and, conversely, cool air is typically dry. As a result, a warm, breezy day speeds evaporation when you hang your laundry outside to dry.

Water vapor influences the density of air. The addition of water vapor decreases the density of air because water vapor has a lower density than air. Thus, humid air is less dense than dry air.

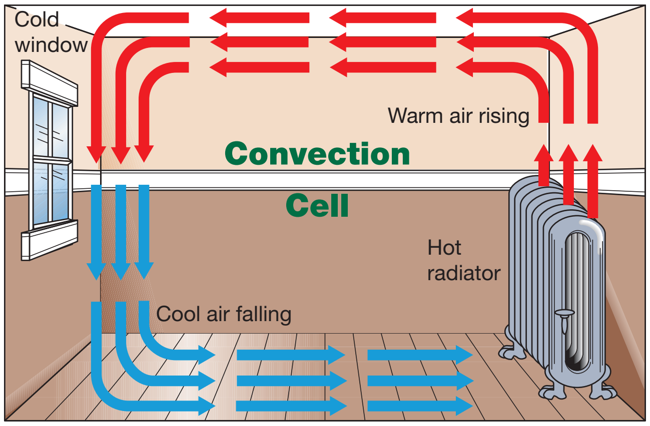


FIGURE 6.6 Convection in a room. A circular-moving loop of air (a convection cell) is caused by warm air rising and cool air sinking.

Atmospheric Pressure

Atmospheric pressure is 1.0 atmosphere[2] (14.7 pounds per square inch) at sea level and decreases with increasing altitude. Atmospheric pressure depends on the weight of the column of air above. For instance, a thick column of air produces higher atmospheric pressure than a thin column of air. An analogy to this is water pressure in a swimming pool: The thicker the column of water above, the higher the water pressure. Thus, the highest pressure in a pool is at the bottom of the deep end.

Similarly, the thicker column of air at sea level means air pressure is high at sea level and decreases with increasing elevation. When sealed bags of potato chips or pretzels are taken to a high elevation, the pressure is much lower than where they were sealed, sometimes causing the bags to burst! You may also have experienced this change in pressure when your ears "popped" during the takeoff or landing of an airplane or while driving on steep mountain roads.

Changes in atmospheric pressure cause air movement as a result of changes in the molecular density of the air. The general relationship is shown in Figure 6.7, which indicates that:

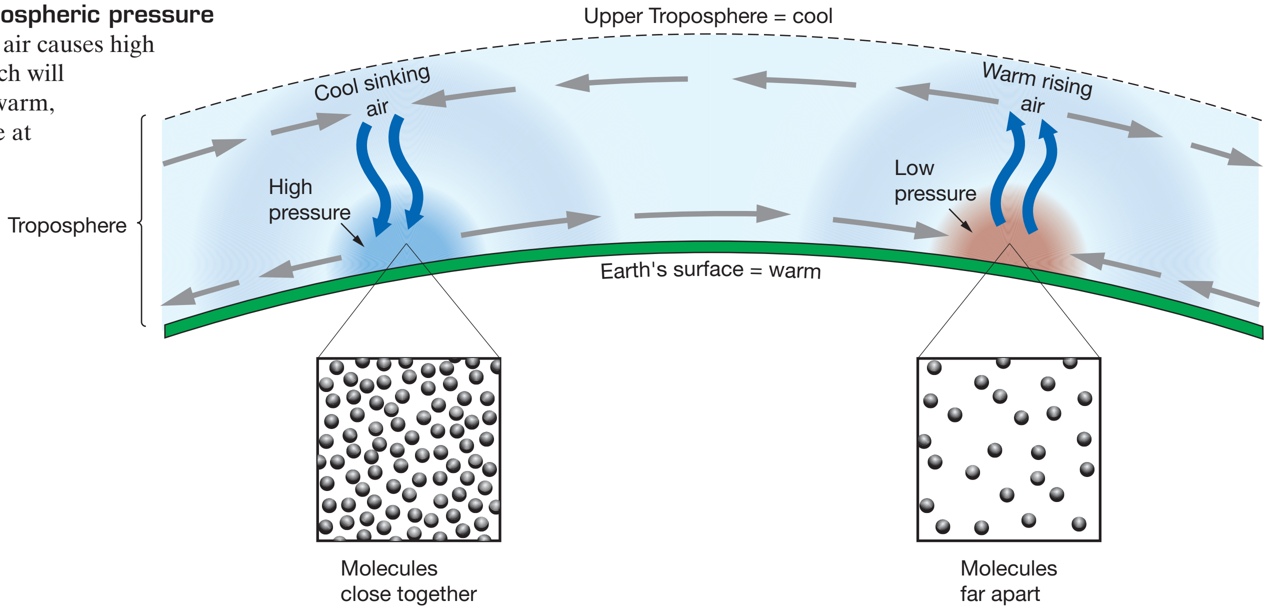
- A column of cool, dense air causes high pressure at the surface, which will lead to sinking air (movement *toward* the surface and compression).
- A column of warm, less dense air causes low pressure at the surface, which will lead to rising air (movement *away from* the surface and expansion).

In addition, sinking air tends to warm because of its compression, while rising air tends to cool due to expansion. Note that there are complex relationships among air composition, temperature, density, water vapor content, and pressure.

Movement of the Atmosphere

Air *always* moves from high-pressure regions toward low-pressure regions. This moving air is called **wind**. If a balloon is inflated and let go, what happens to the air inside the balloon? It rapidly escapes, moving from a high-pressure region

FIGURE 6.7 High and low atmospheric pressure zones. A column of cool, dense air causes high pressure at the surface (*left*), which will lead to sinking air. A column of warm, less dense air causes low pressure at the surface (*right*), which will lead to rising air.



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[2] The *atmosphere* is a unit of pressure; 1.0 atmosphere is the average pressure exerted by the overlying atmosphere at sea level and is equivalent to 760 millimeters of mercury, 101,300 Pascal, or 1013 millibars.

inside the balloon (caused by the balloon pushing on the air inside) to the lower-pressure region outside the balloon.

An Example: A Nonspinning Earth

Imagine for a moment that Earth is not spinning on its axis but that the Sun rotates around Earth, with the Sun directly above Earth's equator at all times (Figure 6.8). Because more solar radiation is received along the equator than at the poles, the air at the equator in contact with Earth's surface is warmed. This warm, moist air rises, creating low pressure at the surface. This rising air cools (see Figure 6.5) and releases its moisture as rain. Thus, a zone of low pressure and much precipitation occurs along the equator.

As the air along the equator rises, it reaches the top of the troposphere and begins to move toward the poles. Because the temperature is much lower at high altitudes, the air cools, and its density increases. This cool, dense air sinks at the poles, creating high pressure at the surface. The sinking air is quite dry because cool air cannot hold much water vapor. Thus, there are high pressure and clear, dry weather at the poles.

Which way will surface winds blow? Air always moves from high pressure to low pressure, so air travels from the high pressure at the poles toward the low pressure at the equator. Thus, there are strong northerly winds in the Northern Hemisphere and strong southerly winds in the Southern Hemisphere.[3] The air warms as it makes its way back to the equator, completing the loop (called a *convection cell* or *circulation cell*; see Figure 6.6).

Is this fictional case of a nonspinning Earth a good analogy for what is really happening on Earth? Actually, it is not, even though the *principles* that drive the physical movement of air remain the same whether Earth is spinning or not. Let's now examine how Earth's spin influences atmospheric circulation.

6.4 How Does the Coriolis Effect Influence Moving Objects?

The **Coriolis effect** changes the intended path of a moving body. Named after Gaspard Gustave de Coriolis, the French engineer who first calculated its influence in 1835, it is often incorrectly called the Coriolis *force*. It does not accelerate the moving body, so it does not influence the body's speed. As a result, it is an effect and not a true force.

The Coriolis effect causes moving objects on Earth to follow curved paths. In the Northern Hemisphere, an object will follow a path to the *right* of its intended direction; in the Southern Hemisphere, an object will follow a path to the *left* of its intended direction. The directions right and left are the *viewer's perspective looking in the direction in which the object is traveling*. For example, the Coriolis effect very slightly influences the movement of a ball thrown between two people. In the Northern Hemisphere, the ball will veer slightly to its right *from the thrower's perspective*.

The Coriolis effect acts on all moving objects. However, it is much more pronounced on objects traveling long distances, especially north or south. This is why the Coriolis effect has a dramatic effect on atmospheric circulation and the movement of ocean currents.

The Coriolis effect is a result of Earth's rotation toward the east. More specifically, the *difference* in the speed of Earth's rotation at different latitudes causes

KEY CONCEPT

The atmosphere is heated from below; its changing temperature, density, water vapor content, and pressure cause atmospheric movement, initiating wind.

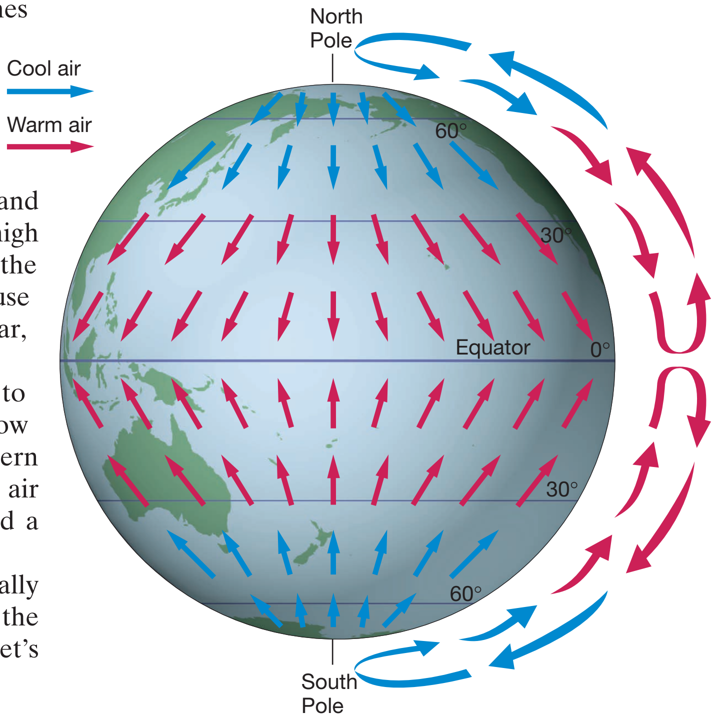

FIGURE 6.8 Atmospheric circulation on a nonspinning Earth. A fictional nonspinning Earth with the Sun rotating around Earth directly above Earth's equator at all times. Arrows show the pattern of winds that would develop due to uneven solar heating on Earth.

STUDENTS SOMETIMES ASK...

Is it true that the Coriolis effect causes water to drain one way in the Northern Hemisphere and the other way in the Southern?

In most cases, no. Theoretically, the water moves too slowly and the distance across a basin in your home is too small to generate a Coriolis-induced whirlpool (vortex) in such a basin. If all other effects are nullified, however, the Coriolis effect comes into play and makes draining water spiral counterclockwise north of the equator and the other way in the Southern Hemisphere (the same direction that hurricanes spin). But the Coriolis effect is extremely weak on small systems like a basin of water. The shape and irregularities of the basin, local slopes, or any external movement can easily outweigh the Coriolis effect in determining the direction in which water drains.

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[3] Notice that winds are named based on the direction *from which they are moving*.

the Coriolis effect. In reality, objects travel along straight-line paths,[4] but Earth rotates underneath them, making the objects appear to curve. Let's look at two examples to help clarify this.

WEB VIDEO

Coriolis Effect on a Merry-Go-Round

Example 1: Perspectives and Frames of Reference on a Merry-Go-Round

A merry-go-round is a useful experimental apparatus with which to test some of the concepts of the Coriolis effect. A merry-go-round is a large circular wheel that rotates around its center. It has bars that people hang onto while the merry-go-round spins, as shown in Figure 6.9.

Imagine that you are on a merry-go-round that is spinning counterclockwise as viewed from above (Figure 6.9). As you are spinning, what will happen to you if you let go of the bar? If you guessed that you would fly off along a straight-line path perpendicular to the merry-go-round (Figure 6.9, *path A*), that's not quite right. Your angular momentum would propel you in a straight line *tangent* to your circular path on the merry-go-round at the point where you let go (Figure 6.9, *path B*). The law of inertia states that a moving object will follow a straight-line path until it is compelled to change that path by other forces. Thus, you would follow a straight-line path (*path B*) until you collide with some object such as other playground equipment or the ground. From the perspective of another person on the merry-go-round, your departure along path B would *appear* to curve to the right due to the merry-go-round's rotation.

Imagine you are again on the merry-go-round, spinning counterclockwise, but you are now joined by another person who is facing you directly but on the opposite side of the merry-go-round. If you were to toss a ball to the other person, what path would it appear to follow? Even though you threw the ball straight at the other person, from *your perspective* the ball's path would appear to curve to the right. That's because the frame of reference (in this example, the merry-go-round) has rotated during the time that it took the ball to reach where the other person had been (Figure 6.9). A person viewing the merry-go-round from directly overhead would observe that the ball did indeed travel along a straight-line path (Figure 6.9, *path C*), just as your path was straight when you let go of the merry-go-round bar. Similarly, the perspective of being on the rotating Earth causes objects to appear to travel along curved paths. This is the Coriolis effect. The merry-go-round spinning in a counterclockwise direction is analogous to the Northern Hemisphere because, as viewed from above the North Pole, Earth is spinning counterclockwise. Thus, moving objects appear to follow curved paths to the *right* of their intended direction in the Northern Hemisphere.

If the other person on the merry-go-round had thrown a ball toward you, it would also appear to have curved. From the perspective of the other person, the ball would appear to curve to its right, just as the ball you threw curved. From your perspective, however, the ball thrown toward you would appear to curve to its *left*. The perspective to keep in mind when considering the Coriolis effect is the one *looking in the same direction that the object is moving*.

To simulate the Southern Hemisphere, the merry-go-round would need to rotate in a *clockwise* direction, which is analogous to Earth when viewed from above the South Pole. Thus, moving objects appear to follow curved paths to the *left* of their intended direction in the Southern Hemisphere.

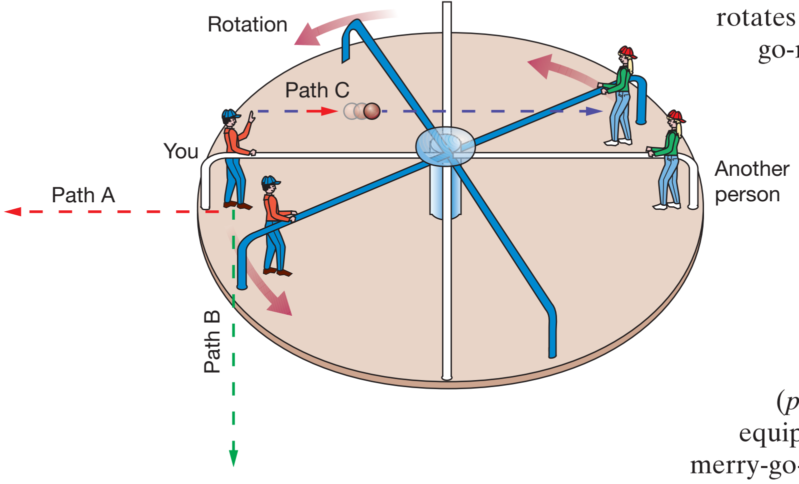

FIGURE 6.9 A merry-go-round spinning counterclockwise as viewed from above. See text for description of paths *A*, *B*, and *C*.

STUDENTS SOMETIMES ASK . . .

If Earth is spinning so fast, why don't we feel it?

Despite Earth's constant rotation, we have the illusion that Earth is still. The reason that we don't feel the motion is because Earth rotates smoothly and quietly, and the atmosphere moves along with us. Thus, all sensations we receive tell us there is no motion and the ground is comfortably at rest— even though most of the United States is continually moving at speeds greater than 800 kilometers (500 miles) per hour!

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[4] Newton's first law of motion (the law of inertia) states that every body persists in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by forces imposed upon it.

Example 2: A Tale of Two Missiles

The distance that a point on Earth has to travel in a day is shorter with increasing latitude. A location near the pole, for example, travels in a circle not nearly as far in a day as will an area near the equator. Because both areas travel their respective distances in one day, the velocity of the two areas must not be the same. Figure 6.10a shows that as Earth rotates on its axis, the velocity decreases with latitude, ranging from more than 1600 kilometers (1000 miles) per hour at the equator to 0 kilometers per hour at the poles. *This change in velocity with latitude is the true cause of the Coriolis effect*. The following example illustrates how velocity changes with latitude.

Imagine that we have two missiles that fly in straight lines toward their destinations. For simplicity, assume that the flight of each missile takes one hour regardless of the distance flown. The first missile is launched from the North Pole toward New Orleans, Louisiana, which is at 30 degrees north latitude (Figure 6.10b). Does the missile land in New Orleans? Actually, no. Earth rotates eastward at 1400 kilometers (870 miles) per hour along the 30 degrees latitude line (Figure 6.10a), so the missile lands somewhere near El Paso, Texas, 1400 kilometers west of its target. From your perspective at the North Pole, the path of the missile appears to curve *to its right* in accordance with the Coriolis effect. In reality, New Orleans has moved out of the line of fire due to Earth's rotation.

The second missile is launched toward New Orleans from the Galápagos Islands, which are directly south of New Orleans along the equator (Figure 6.10b). From their position on the equator, the Galápagos Islands are moving east at 1600 kilometers (1000 miles) per hour, 200 kilometers (124 miles) per hour faster than New Orleans (Figure 6.10a). At takeoff, therefore, the missile is also moving toward the east 200 kilometers per hour faster than New Orleans. Thus, when the missile returns to Earth one hour later at the latitude of New Orleans, it will land offshore of Alabama, 200 kilometers east of New Orleans. Again, from your perspective on the Galápagos Islands, the missile appears to curve *to its right*. Keep in mind that both of these missile examples ignore friction, which would greatly reduce the amount the missiles deflect to the right of their intended courses.

STUDENTS SOMETIMES ASK . . .

Why are space missions launched from low-latitude regions?

The reason that the United States launches its space missions from Florida is to take advantage of Earth's additional rotational speed at lower latitudes (note arrows in Figure 6.10a), thereby giving space vehicles more momentum once they get into space. And, the further south you go, the more momentum the rockets naturally obtain; that's why some countries (such as France) launch rockets from their territories in tropical islands. In fact, the multinational company Sea Launch currently operates a floating launching pad along the equator about 1600 kilometers (1000 miles) south of Hawaii.

Coriolis Effect

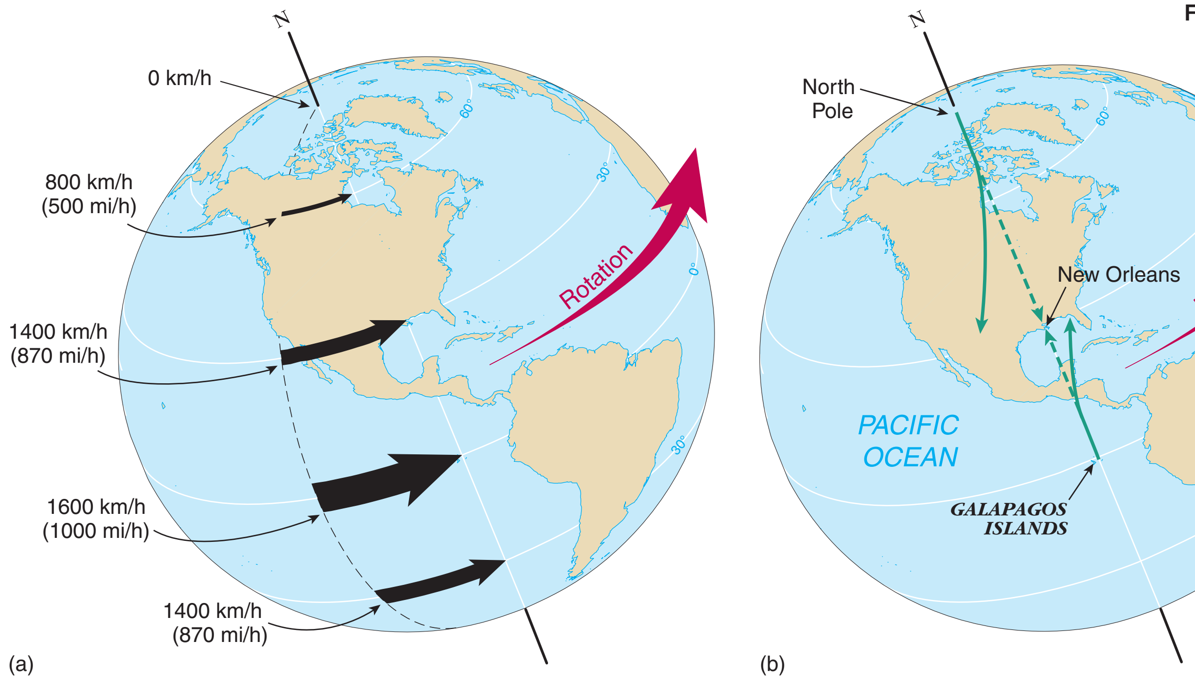


FIGURE 6.10 The Coriolis effect and missile paths. (a) The velocity of any point on earth varies with latitude from about 1600 kilometers (1000 miles) per hour at the equator to 0 kilometers per hour at either pole. **(b)** The paths of missiles shot toward New Orleans from the North Pole and from the Galápagos Islands on the equator. Dashed lines indicate intended paths; solid lines indicate paths that the missiles would travel as viewed from Earth's surface.

STUDENTS SOMETIMES ASK . . .

I've heard that the Coriolis effect is really a force but it is often described as a fictitious force. What is a fictitious force?

The forces you feel in a moving car—those that push you back into your seat when the driver steps on the gas or throw you sideways when the car makes sharp turns—are everyday examples of fictitious forces. In general, these influences arise because the natural frame of reference for a given situation (such as the car) is itself accelerating.

A classic example of these types of apparent influences involves the Coriolis "force" and a pendulum. Consider a back-and-forth swinging pendulum that is suspended directly over the North Pole. To an earthly observer, it would appear to rotate 360 degrees every day and thus would seem to be acted upon by a sideways force (that is, perpendicular to the plane of swing). If you viewed this pendulum from a stationary point in outer space, however, it would appear to swing in a single, fixed plane while Earth turned underneath it. From this outer-space perspective, there is no sideways force deflecting the pendulum's sway. That is why the somewhat pejorative term "fictitious" is attached to this force and also why Coriolis is more properly termed an effect (not a true force). Similarly, in the car, no real force pushes you back into your seat, your senses notwithstanding; what you feel is the moving frame of reference caused by the car's acceleration.

KEY CONCEPT

The Coriolis effect causes moving objects to curve to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. It is at its maximum at the poles and is zero at the equator.

Changes in the Coriolis Effect with Latitude

The first missile (shot from the North Pole) missed the target by 1600 kilometers (1000 miles), while the second missile (shot from the Galápagos Islands) missed its target by only 200 kilometers (124 miles). What was responsible for the difference? Not only does the rotational velocity of points on Earth range from 0 kilometers per hour at the poles to more than 1600 kilometers (1000 miles) per hour at the equator, but the *rate of change* of the rotational velocity (per degree of latitude) increases as the pole is approached from the equator.

For example, the rotational velocity differs by 200 kilometers (124 miles) per hour between the equator (0 degrees) and 30 degrees north latitude. From 30 degrees north latitude to 60 degrees north latitude, however, the rotational velocity differs by 600 kilometers (372 miles) per hour. Finally, from 60 degrees north latitude to the North Pole (where the rotational velocity is zero), the rotational velocity differs by more than 800 kilometers (500 miles) per hour.

Thus, the maximum Coriolis effect is at the poles, and there is no Coriolis effect at the equator. The magnitude of the Coriolis effect depends much more, however, on the length of time the object (such as an air mass or ocean current) is in motion. Even at low latitudes, where the Coriolis effect is small, a large Coriolis deflection is possible if an object is in motion for a long time. In addition, because the Coriolis effect is caused by the *difference* in velocity of different latitudes on Earth, there is no Coriolis effect for those objects moving due east or due west along the equator.

For a summary of the Coriolis effect, see Web Table 6.1.

6.5 What Global Atmospheric Circulation Patterns Exist?

Figure 6.11 shows atmospheric circulation and the corresponding wind belts on a spinning Earth, which presents a more complex pattern than that of the fictional nonspinning Earth (Figure 6.8).

Circulation Cells

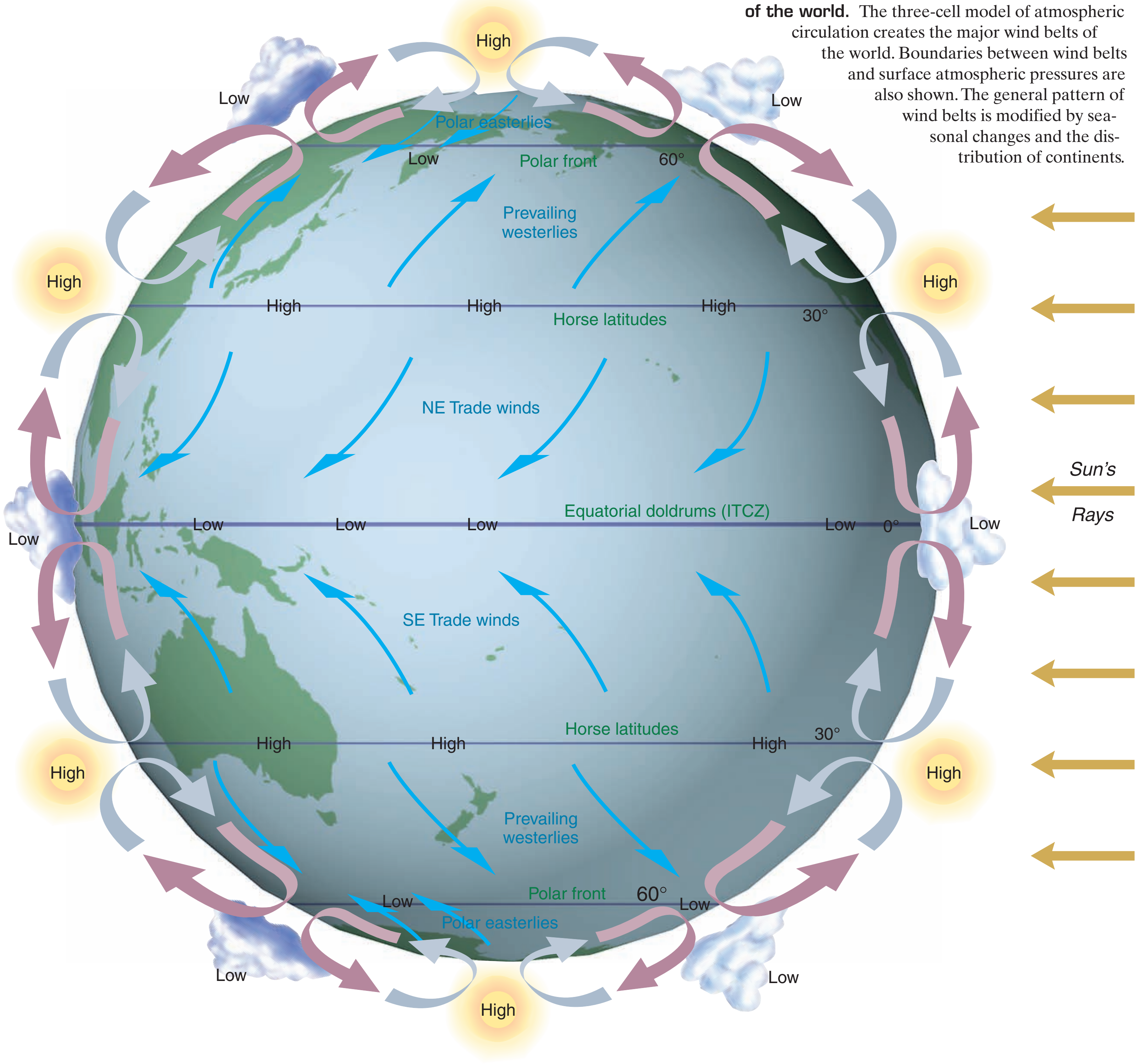
The greater heating of the atmosphere over the equator causes the air to expand, to decrease in density, and to rise. As the air rises, it cools by expansion because the pressure is lower, and the water vapor it contains condenses and falls as rain in the equatorial zone. The resulting dry air mass travels north or south of the equator. Around 30 degrees north and south latitude, the air cools off enough to become denser than the surrounding air, so it begins to descend, completing the loop (Figure 6.11). These circulation cells are called **Hadley cells** after noted English meteorologist George Hadley (1685–1768).

In addition to Hadley cells, each hemisphere has a **Ferrel cell** between 30 and 60 degrees latitude and a **polar cell** between 60 and 90 degrees latitude. The Ferrel cell—named after American meteorologist William Ferrel (1817–1891), who invented the three-cell per hemisphere model for atmospheric circulation—is not driven solely by differences in solar heating; if it were, air within it would circulate in the opposite direction. Similar to the movement of interlocking gears, the Ferrel cell moves in the direction that coincides with the movement of the two adjoining circulation cells.

Pressure

A column of cool, dense air moves *toward* the surface and creates high pressure. The descending air at about 30 degrees north and south latitude creates high-pressure zones called the **subtropical highs**. Similarly, descending air at the poles creates high-pressure regions called the **polar highs**.

FIGURE 6.11 Atmospheric circulation and wind belts of the world. The three-cell model of atmospheric circulation creates the major wind belts of the world. Boundaries between wind belts and surface atmospheric pressures are also shown. The general pattern of wind belts is modified by seasonal changes and the distribution of continents.



What kind of weather is experienced in these high-pressure areas? Descending air is quite dry and it tends to warm under its own weight, so these areas typically experience dry, clear, fair conditions. The conditions are not necessarily warm (such as at the poles)—just dry and associated with clear skies.

A column of warm, low density air rises *away* from the surface and creates low pressure. Thus, rising air creates a band of low pressure at the equator—the **equatorial low**—and at about 60 degrees north and south latitude—the **subpolar low**.

web animation

Global Wind Patterns

The weather in areas of low pressure is dominated by cloudy conditions with lots of precipitation, because rising air cools and cannot hold its water vapor.

WEB VIDEO

Satellite Video of Major Wind Belts

Wind Belts

The lowermost portion of the circulation cells—that is, the part that is closest to the surface—generates the major wind belts of the world. The masses of air that move across Earth's surface from the subtropical high-pressure belts toward the equatorial low-pressure belt constitute the **trade winds**. These steady winds are named from the term *to blow trade*, which means to blow in a regular course. If Earth did not rotate, these winds would blow in a north–south direction. In the Northern Hemisphere, however, the **northeast trade winds** curve to the right due to the Coriolis effect and blow *from northeast to southwest*. In the Southern Hemisphere, on the other hand, the **southeast trade winds** curve to the left due to the Coriolis effect and blow *from southeast to northwest*.

Some of the air that descends in the subtropical regions moves along Earth's surface to higher latitudes as the **prevailing westerly wind belts**. Because of the Coriolis effect, the prevailing westerlies blow from southwest to northeast in the Northern Hemisphere and from northwest to southeast in the Southern Hemisphere.

Air moves away from the high pressure at the poles, too, producing the **polar easterly wind belts**. The Coriolis effect is maximized at high latitudes, so these winds are deflected strongly. The polar easterlies blow from the northeast in the Northern Hemisphere, and from the southeast in the Southern Hemisphere. When the polar easterlies come into contact with the prevailing westerlies near the subpolar low pressure belts (at 60 degrees north and south latitude), the warmer, less dense air of the prevailing westerlies rises above the colder, more dense air of the polar easterlies.

Boundaries

The boundary between the two trade wind belts along the equator is known as the **doldrums** (*doldrum* = dull) because, long ago, sailing ships were becalmed there by the lack of winds. Sometimes stranded for days or weeks, the situation was unfortunate but not life-threatening: Daily rain showers supplied sailors with plenty of freshwater. Today, meteorologists refer to this region as the **Intertropical Convergence Zone (ITCZ)**, because it is the region between the tropics where the trade winds converge (Figure 6.11).

The boundary between the trade winds and the prevailing westerlies (centered at 30 degrees north or south latitude) is known as the **horse latitudes**. Sinking air in these regions causes high atmospheric pressure (associated with the *subtropical high pressure*) and results in clear, dry, and fair conditions. Because the air is sinking, the horse latitudes are known for surface winds that are light and variable.

The boundary between the prevailing westerlies and the polar easterlies at 60 degrees north or south latitude is known as the **polar front**. This is a battleground for different air masses, so cloudy conditions and lots of precipitation are common here.

Clear, dry, fair conditions are associated with the high pressure at the poles, so precipitation is minimal. The poles are often classified as cold deserts because the annual precipitation is so low.

Table 6.2 summarizes the characteristics of global wind belts and boundaries.

STUDENTS SOMETIMES ASK . . .

What is the origin of the name horse latitudes?

The term *horse latitudes* supposedly originates from the days when Spanish sailing vessels transported horses across the Atlantic to the West Indies. Ships would often become becalmed in mid-ocean due to the light winds in these latitudes, thus severely prolonging the voyage; the resulting water shortages would make it necessary for crews to dispose of their horses overboard (see the chapter-opening quote). Alternatively, the term might also have originated by seamen who were paid an advance called the "dead horse" before a long voyage. A few months into the voyage, the "dead horse" was officially worked off; this was also about the same time sailing vessels were stuck in the middle of the ocean without wind, so these regions became known as the horse latitudes.

Circulation Cells: Idealized or Real?

The three-cell model of atmospheric circulation first proposed by Ferrel provides a simplified model of the general circulation pattern on Earth. This circulation model is idealized and does not always match the complexities observed

TABLE 6.2 CHARACTERISTICS OF WIND BELTS AND BOUNDARIES

Region (north or south latitude)	Name of wind belt or boundary	Atmospheric pressure	Characteristics
Equatorial (0–5 degrees)	Doldrums (boundary)	Low	Light, variable winds. Abundant cloudiness and much precipitation. Breeding ground for hurricanes.
5–30 degrees	Trade winds (wind belt)	—	Strong, steady winds, generally from the east.
30 degrees	Horse latitudes (boundary)	High	Light, variable winds. Dry, clear, fair weather with little precipitation. Major deserts of the world.
30–60 degrees	Prevailing westerlies (wind belt)	—	Winds generally from the west. Brings storms that influence weather across the United States.
60 degrees	Polar front (boundary)	Low	Variable winds. Stormy, cloudy weather year round.
60–90 degrees	Polar easterlies (wind belt)	—	Cold, dry winds generally from the east.
Poles (90 degrees)	Polar high pressure (boundary)	High	Variable winds. Clear, dry, fair conditions, cold temperatures, and minimal precipitation. Cold deserts.

in nature, particularly for the location and direction of motion of the Ferrel and polar cells. Nonetheless, it generally matches the pattern of major wind belts of the world and provides a general framework for understanding why they exist.

Further, the following factors significantly alter the idealized wind, pressure, and atmospheric circulation patterns illustrated in Figure 6.11:

1. The tilt of Earth's rotation axis, which produces seasons
2. The lower heat capacity of continental rock compared to seawater,[5] which makes the air over continents colder in winter and warmer in summer than the air over adjacent oceans
3. The uneven distribution of land and ocean over Earth's surface, which particularly affects patterns in the Northern Hemisphere

During winter, therefore, the continents usually develop atmospheric high-pressure cells from the weight of cold air centered over them and, during the summer, they usually develop low-pressure cells (Figure 6.12). In fact, such seasonal shifts in atmospheric pressure over Asia cause *monsoon winds*, which have a dramatic effect on Indian Ocean currents and will be discussed in Chapter 7, "Ocean Circulation." In general, however, the patterns of atmospheric high- and low-pressure zones shown in Figure 6.12 corresponds closely to those shown in Figure 6.11.

Global wind belts have had a profound effect on ocean explorations (Box 6.1). The world's wind belts also closely match the pattern of ocean surface currents, which are discussed in Chapter 7, "Ocean Circulation."

KEY CONCEPT

The major wind belts in each hemisphere are the trade winds, the prevailing westerlies, and the polar easterlies. The boundaries between these wind belts include the doldrums, the horse latitudes, the polar front, and the polar high.

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[5] An object that has low heat capacity heats up quickly when heat energy is applied. Recall from Figure 5.7 that water has one of the highest specific heat capacities of common substances.

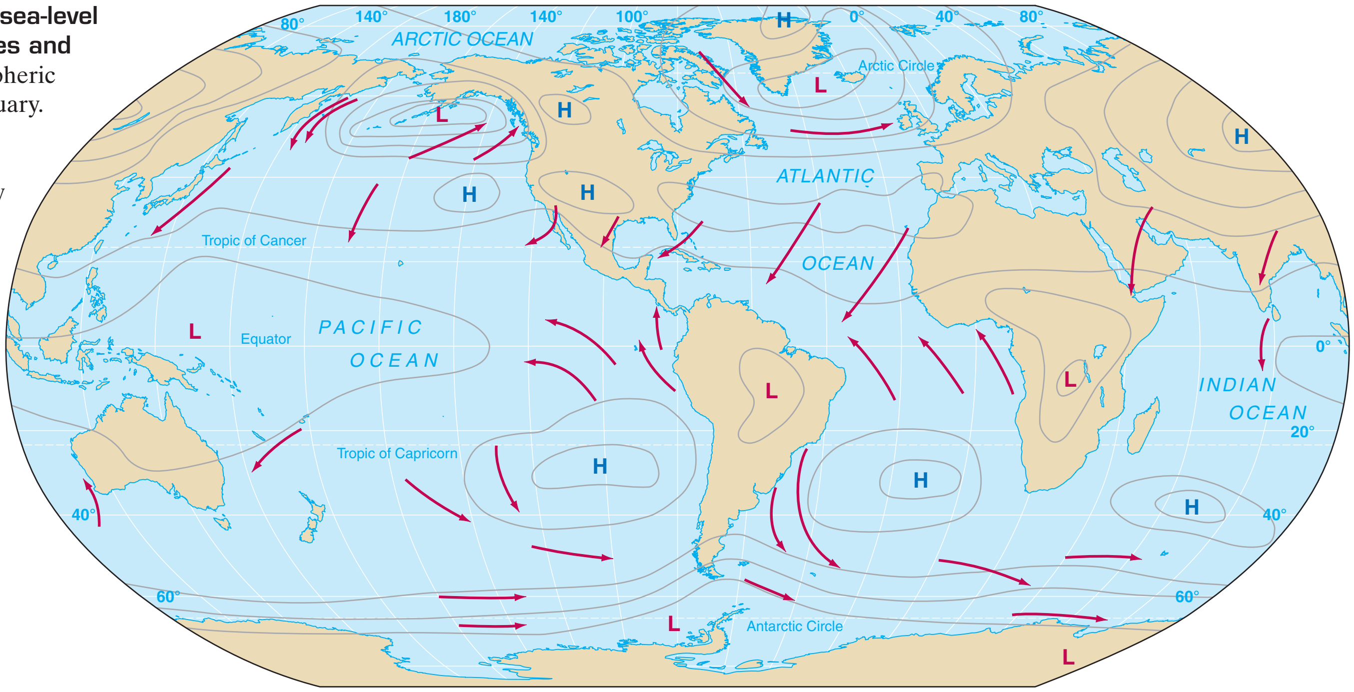

FIGURE 6.12 January sea-level atmospheric pressures and winds. Average atmospheric pressure pattern for January. High (*H*) and low (*L*) atmospheric pressure zones correspond closely to those shown in Figure 6.11 but are modified by the change of seasons and the distribution of continents. Arrows show direction of winds, which move from high- to low-pressure regions.

Seasonal Pressure and Precipitation Patterns

6.6 What Weather and Climate Patterns Does the Ocean Exhibit?

Because of the ocean's huge extent over Earth's surface and also because of water's unusual thermal properties, the ocean dramatically influences global weather and climate patterns.

Weather Versus Climate

Weather describes the conditions of the atmosphere at a given time and place. **Climate** is the long-term average of weather. If we observe the weather conditions in an area over a long period, we can begin to draw some conclusions about its climate. For instance, if the weather in an area is dry over many years, we can say that the area has an arid climate.

Winds

Recall that air always moves from high pressure toward low pressure and that the movement of air is called *wind*. However, as air moves away from high-pressure regions and toward low-pressure regions, the Coriolis effect modifies its direction. In the Northern Hemisphere, for example, air moving from high to low pressure curves to the right and results in a counterclockwise[6] flow of air around low-pressure cells [called **cyclonic** *(kyklon = moving in a circle)* **flow**]. Similarly, as the air leaves the high-pressure region and curves to the right, it establishes a clockwise flow of air around high-pressure cells (called **anticyclonic flow**). Figure 6.13 shows how a screwdriver can help you remember how air moves around high- and low-pressure regions: High pressures are similar to a high screw that needs to be tightened, so a screwdriver would be turned clockwise; low pressures are similar to a tightened screw that needs to be loosened, so a screwdriver would be turned

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[6] These directions are reversed in the Southern Hemisphere.

6.1 HISTORICAL FEATURE

WHY CHRISTOPHER COLUMBUS NEVER SET FOOT ON NORTH AMERICA

The Italian navigator and explorer **Christopher Columbus** is widely credited with discovering North America in the year 1492. However, America was already populated with many natives, and the Vikings predated his voyage to North America by about 500 years. Moreover, the pattern of the major wind belts of the world prevented his sailing ships from reaching continental North America during his four voyages.

Rather than sailing east, Columbus was determined to reach the East Indies (today the country of Indonesia) by sailing west across the Atlantic Ocean. An astronomer in Florence, Italy, named Toscanelli was the first to suggest such a route in a letter to the king of Portugal. Columbus later contacted Toscanelli and was told how far he would have to sail west to reach India. Today, we know that this distance would have carried him just west of North America.

After years of difficulties in initiating the voyage, Columbus received the financial backing of the Spanish monarchs Ferdinand V and Isabella I. He set sail with 88 men and three ships (the *Niña*, the *Pinta*, and the *Santa María*) on August 3, 1492, from the Canary Islands off Africa (Figure 6A). The Canary Islands are located at 28 degrees north latitude and are within the northeast trade winds, which blow steadily from the northeast to the southwest. Instead of sailing directly west, which would have allowed Columbus to reach central Florida, the map in Figure 6A shows that Columbus sailed a more southerly route.

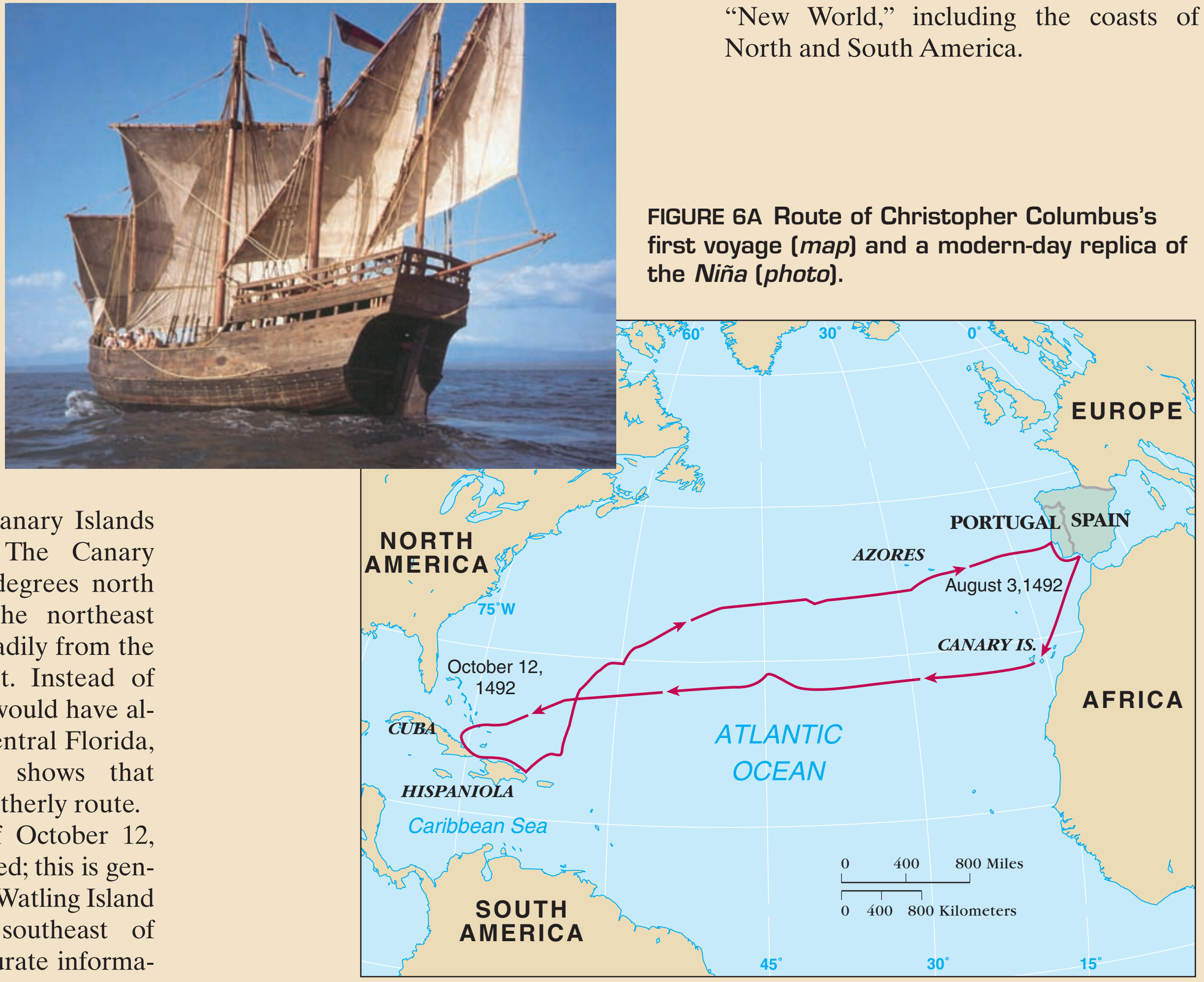

FIGURE 6A Route of Christopher Columbus's first voyage (*map*) and a modern-day replica of the *Niña* (*photo*).

During the morning of October 12, 1492, the first land was sighted; this is generally believed to have been Watling Island in the Bahama Islands southeast of Florida. Based on the inaccurate information he had been given, Columbus was convinced that he had arrived in the East Indies and was somewhere near India. Consequently, he called the inhabitants "Indians," and the area is known today as the West Indies. Later during this voyage, he explored the coasts of Cuba and Hispaniola (the island comprising modern-day Haiti and the Dominican Republic).

On his return journey, he sailed to the northeast and picked up the prevailing westerlies, which transported him away from North America and toward Spain. Upon his return to Spain and the announcement of his discovery, additional voyages were planned. Columbus made three more trips across the Atlantic Ocean, following similar paths through the Atlantic. Thus, his ships were controlled by the trade winds on the outbound voyage and the prevailing westerlies on the return trip. During his next voyage, in 1493, Columbus explored Puerto Rico and the Leeward Islands and established a colony on Hispaniola. In 1498, he explored Venezuela and landed on South America, unaware that it was a new continent to Europeans. On his last voyage in 1502, he reached Central America.

Although he is today considered a master mariner, he died in neglect in 1506, still convinced that he had explored islands near India. Even though he never set foot on the North American mainland, his journeys inspired other Spanish and Portuguese navigators to explore the "New World," including the coasts of North and South America.

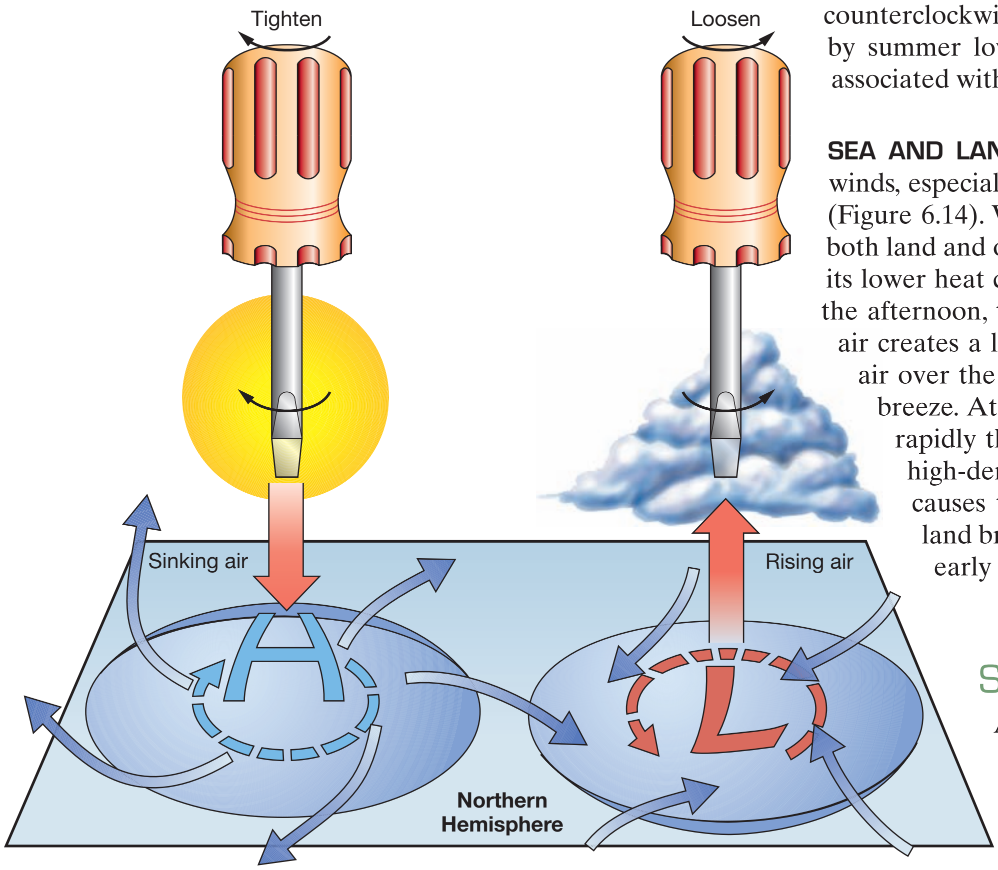

FIGURE 6.13 High- and low-pressure regions and air flow. As air moves away from a high-pressure region (H) toward a low-pressure region (L), the Coriolis effect causes the air to curve to the right in the Northern Hemisphere. This results in clockwise winds around high-pressure regions (anticyclonic flow) and counterclockwise winds around low-pressure regions (cyclonic flow). One way to remember this is to think of high pressures as being similar to a high screw that needs tightening (clockwise motion) and low pressures as being similar to a tightened screw that needs loosening (counterclockwise motion).

counterclockwise. Because winter high-pressure cells are replaced by summer low-pressure cells over the continents, wind patterns associated with continents often reverse themselves seasonally.

SEA AND LAND BREEZES Other factors that influence regional winds, especially in coastal areas, are **sea breezes** and **land breezes** (Figure 6.14). When an equal amount of solar energy is applied to both land and ocean, the land heats up about five times more due to its lower heat capacity. The land heats the air around it and, during the afternoon, the warm, low-density air over the land rises. Rising air creates a low-pressure region over the land, pulling the cooler air over the ocean toward land, creating what is known as a sea breeze. At night, the land surface cools about five times more rapidly than the ocean and cools the air around it. This cool, high-density air sinks, creating a high-pressure region that causes the wind to blow from the land. This is known as a land breeze, and it is most prominent in the late evening and early morning hours.

Storms and Fronts

At very high and very low latitudes, there is little daily and minor seasonal change in weather.[7] Equatorial regions are usually warm, damp, and typically calm, because the dominant direction of air movement in the doldrums is upward. Midday rains are common, even during the supposedly "dry" season. It is within the *middle latitudes* between 30 and 60 degrees north or south latitude where storms are common.

Storms are atmospheric disturbances characterized by strong winds, precipitation, and often thunder and lightning. Due to the seasonal change of pressure systems over continents, air masses from the high and low latitudes may move into the middle latitudes, meet, and produce severe storms. **Air masses** are large volumes of air that have a definite area of origin and distinctive characteristics. Several air masses influence the United States, including polar air masses and tropical air masses (Figure 6.15). Some air masses originate over land (c = continental) and are therefore dryer, but most originate over the sea (m = maritime) and are moist. Some are colder (P = polar; A = Arctic) and some are warm (T = tropical). Typically, the United States is influenced more by polar air masses during the winter and more by tropical air masses during the summer.

As polar and tropical air masses move into the middle latitudes, they also move gradually in an easterly direction. A **warm front** is the contact between a warm air mass moving into an area occupied by cold air. A **cold front** is the contact between a cold air mass moving into an area occupied by warm air (Figure 6.16).

These confrontations are brought about by the movement of the **jet stream**, which is a narrow, fast-moving, easterly flowing air mass. It exists above the middle latitudes just below the top of the troposphere, centered at an altitude of about 10 kilometers (6 miles). It usually follows a wavy path and may cause unusual weather by steering a polar air mass far to the south or a tropical air mass far to the north.

web animation

Cyclones and Anticyclones

web animation

Cold Fronts and Warm Fronts

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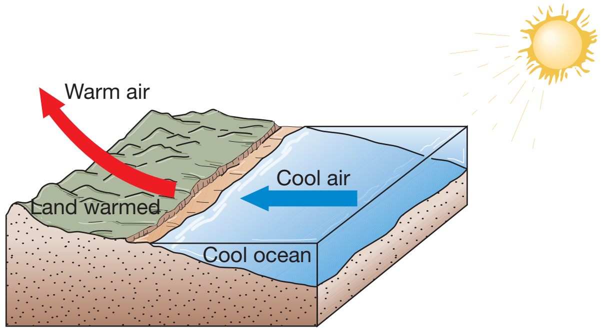
[7] In fact, in equatorial Indonesia, the vocabulary of Indonesians doesn't include the word *seasons*.

Regardless of whether a warm front or cold front is produced, the warmer, less-dense air always rises above the denser cold air. The warm air cools as it rises, so its water vapor condenses as precipitation. A cold front is usually steeper, and the temperature difference across it is greater than a warm front. Therefore, rainfall along a cold front is usually heavier and briefer than rainfall along a warm front.

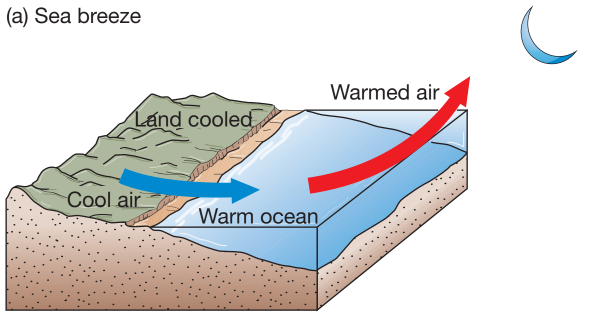
Tropical Cyclones (Hurricanes)

Tropical cyclones (*kyklon* = moving in a circle) are huge rotating masses of low pressure characterized by strong winds and torrential rain. They are the largest storm systems on Earth, though they are not associated with any fronts. In North and South America, tropical cyclones are called **hurricanes** (*Huracan* = Taino god of wind); in the western North Pacific Ocean, they are called **typhoons** (*tai-fung* = great wind); and in the Indian Ocean, they are called **cyclones**. No matter what they are called, tropical cyclones can be highly destructive. In fact, the energy contained in a *single* hurricane is greater than that generated by all energy sources in the United States over the past 20 years.

ORIGIN Remarkably, what powers tropical storms is the release of vast amounts of water's *latent heat of condensation*[8] that is carried within water vapor and is released as water condenses to form clouds in a hurricane. A tropical cyclone begins as a low-pressure cell that breaks away from the equatorial low-pressure belt and grows as it picks up heat energy in the



(a) Sea breeze



(b) Land breeze

FIGURE 6.14 Sea and land breezes. **(a)** Sea breezes occur when air warmed by the land rises and is replaced by cool air from the ocean. **(b)** Land breezes occur when the land has cooled, causing dense air to sink and flow toward the warmer ocean.

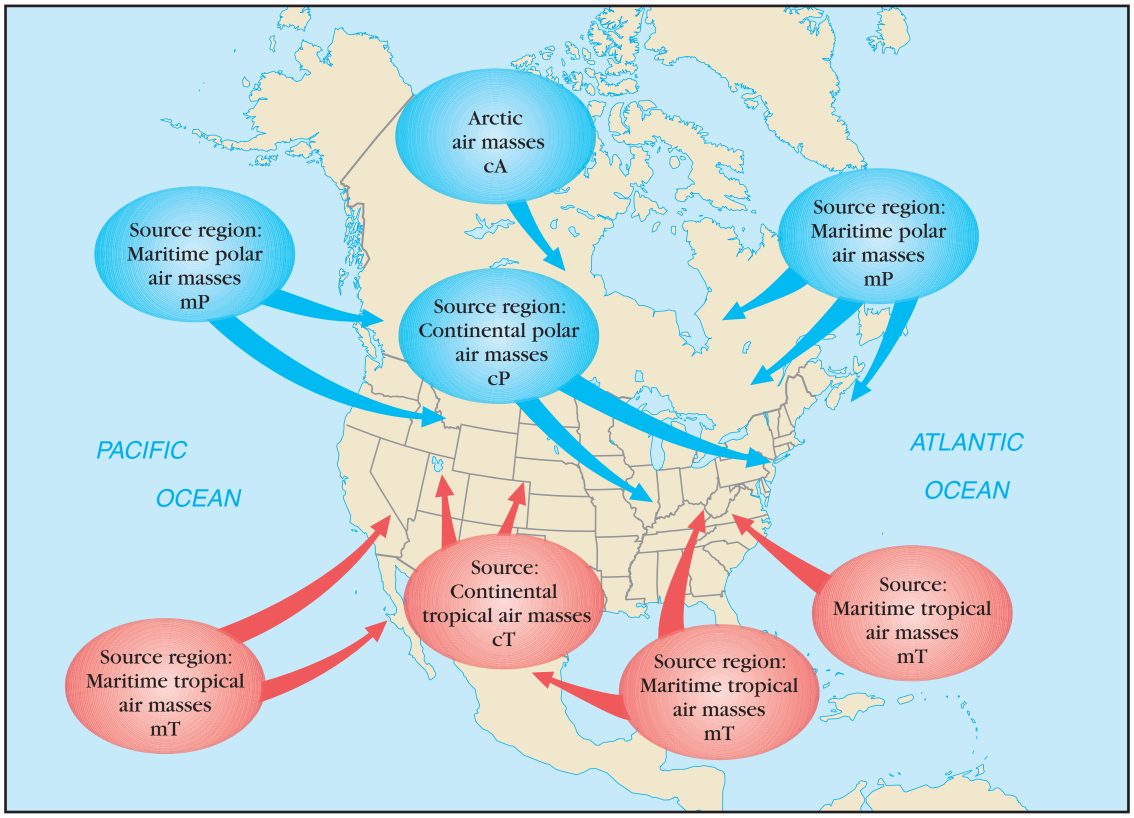


FIGURE 6.15 Air masses that affect U.S. weather. Polar air masses are shown in blue, and tropical air masses are shown in red. Air masses are classified based on their source region: The designation continental (c) or maritime (m) indicates moisture content, whereas polar (P), Arctic (A), and tropical (T) indicate temperature conditions.

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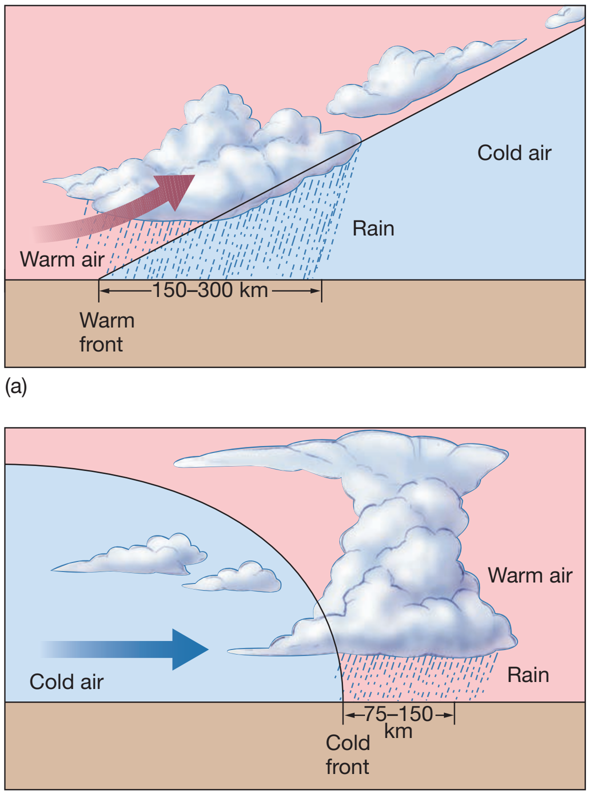
[8] For a discussion of water's latent heats, see Chapter 5.



(a)

(b)

FIGURE 6.16 Warm and cold fronts. Cross sections through a gradually rising warm front **(a)** and a steeper cold front **(b)**. With both fronts, warm air rises and precipitation is produced.

following manner. Surface winds feed moisture (in the form of water vapor) into the storm. When water evaporates, it stores tremendous amounts of heat in the form of latent heat of evaporation. When water vapor condenses into a liquid (in this case, clouds and rain), it releases this stored heat—latent heat of condensation—into the surrounding atmosphere, which causes the atmosphere to warm and the air to rise. This rising air causes surface pressure to decrease, drawing additional warm moist surface air into the storm. This air, as it rises and cools, condenses into clouds and releases even more latent heat, further powering the storm and continuously repeating itself, each time intensifying the storm.

Tropical storms are classified according to their maximum sustained wind speed:

- If winds are less than 61 kilometers (38 miles) per hour, the storm is classified as a *tropical depression*.
- If winds are between 61 and 120 kilometers (38 and 74 miles) per hour, the storm is called a *tropical storm*.
- If winds exceed 120 kilometers (74 miles) per hour, the storm is a *tropical cyclone*.

The **Saffir-Simpson Scale** of hurricane intensity (Table 6.3) further divides tropical cyclones into categories based on wind speed and damage. In some cases, in fact, the wind in tropical cyclones attains speeds as high as 400 kilometers (250 miles) per hour!

Worldwide, about 100 storms grow to hurricane status each year. The conditions needed to create a hurricane are as follows:

- Ocean water with a temperature greater than 25°C (77°F), which provides an abundance of water vapor to the atmosphere through evaporation.
- Warm, moist air, which supplies vast amounts of latent heat as the water vapor in the air condenses and fuels the storm.

TABLE 6.3 THE SAFFIR-SIMPSON SCALE OF HURRICANE INTENSITY

	Wind speed		Typical storm surge (sea level height above normal)		
Category	**(km/hr)**	**(mi/hr)**	**(meters)**	**(feet)**	**Damage**
1	120–153	74–95	1.2–1.5	4–5	Minimal: Minor damage to buildings
2	154–177	96–110	1.8–2.4	6–8	Moderate: Some roofing material, door, and window damage; some trees blown down
3	178–209	111–130	2.7–3.7	9–12	Extensive: Some structural damage and wall failures; foliage blown off trees and large trees blown down
4	210–249	131–155	4.0–5.5	13–18	Extreme: More extensive structural damage and wall failures; most shrubs, trees, and signs blown down
5	>250	>155	>5.8	>19	Catastrophic: Complete roof failures and entire building failures common; all shrubs, trees, and signs blown down; flooding of lower floors of coastal structures

- The Coriolis effect, which causes the hurricane to spin counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. No hurricanes occur directly on the equator because the Coriolis effect is zero there.[9]

Hurricanes

These conditions are found during the late summer and early fall, when the tropical and subtropical oceans are at their maximum temperature. Even though hurricanes sometimes form outside of hurricane season (Box 6.2), the official Atlantic basin hurricane season is from June 1 to November 30 each year. These dates conventionally delimit the period when most tropical cyclones form in the Atlantic basin.

MOVEMENT When hurricanes are initiated in the low latitudes, they are affected by the trade winds and generally move from east to west across ocean basins. Hurricanes typically last from 5 to 10 days and sometimes migrate into the middle latitudes (Figure 6.17). In rare cases, hurricanes have done considerable damage to the northeast United States and have even affected Nova Scotia, Canada. Figure 6.17 also shows how hurricanes are affected by the Coriolis effect: In the Northern Hemisphere, they curve to the right and in the Southern Hemisphere, they curve to the left. Moreover, this serves to carry them out of the tropics and over land or cooler water, where their energy source is cut off, eventually causing the hurricane to dissipate.

The diameter of a typical hurricane is less than 200 kilometers (124 miles), although extremely large hurricanes can exceed diameters of 800 kilometers (500 miles). As air moves across the ocean surface toward the low-pressure center, it is drawn up around the **eye of the hurricane** (Figure 6.18). The air in the vicinity of the eye spirals upward, so horizontal wind speeds may be less than 15 kilometers (25 miles) per hour. The eye of the hurricane, therefore, is usually calm. Hurricanes are composed of spiral rain bands where intense rainfall caused by severe thunderstorms can produce tens of centimeters (several inches) of rainfall per hour.

TYPES OF DESTRUCTION Destruction from hurricanes is caused by high winds and flooding from intense rainfall. **Storm surge**, however, causes the majority of a hurricane's coastal destruction. In fact, storm surge is responsible for 90% of the deaths associated with hurricanes.

When a hurricane develops over the ocean, its low-pressure center produces a low "hill" of water (Figure 6.19). As the hurricane migrates across the open ocean, the hill moves with it. As the hurricane approaches shallow water near shore, the portion of the hill over which the wind is blowing shoreward produces a mass of elevated, wind-driven water. This mass of water—the storm surge—can be as high as 12 meters (40 feet), resulting in a dramatic increase in sea level at the shore, large storm waves, and tremendous destruction to low-lying coastal areas (particularly if it occurs at high tide). In addition, the area of the coast that is hit with the right front quadrant of the hurricane—where onshore winds further pile up water—experiences the most severe storm surge (Figure 6.19). Table 6.3 shows typical storm surge heights associated with Saffir-Simpson hurricane intensities.

HISTORIC DESTRUCTION Periodic destruction from hurricanes occurs along the East Coast and the Gulf Coast regions of the United States. In fact, the most deadly natural disaster in U.S. history was caused by a hurricane that struck Galveston Island, Texas, in September 1900. Galveston Island is a thin strip of

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[9] An unusual confluence of weather conditions in 2001 created the first-ever documented instance of a tropical cyclone almost directly over the equator. Statistical models indicate that such an event occurs only once every 300–400 years.

6.2 FOCUS ON THE ENVIRONMENT

THE RECORD-BREAKING 2005 ATLANTIC HURRICANE SEASON: HURRICANES KATRINA, RITA, AND WILMA

Although the official Atlantic hurricane season extends each year from June 1 to November 30, the 2005 Atlantic hurricane season persisted into January 2006 and was the most active season on record, shattering numerous records. For example, a record 27 named tropical storms formed, of which a record 15 became hurricanes. Of these, seven strengthened into major hurricanes, a record-tying five became Category 4 hurricanes and a record four reached Category 5 strength, the highest categorization for hurricanes on the Saffir-Simpson Scale of hurricane intensity (see Table 6.3). For the first time ever, NOAA's National Hurricane Center, which oversees the naming of Atlantic Hurricanes, ran out of the usual names for storms and resorted to naming storms using the Greek alphabet.

The most notable storms of the 2005 season were the five Category 4 and Category 5 hurricanes: Dennis, Emily, Katrina, Rita, and Wilma. These storms made a combined twelve landfalls as major hurricanes (Category 3 strength or higher) throughout Cuba, Mexico, and the Gulf Coast of the United States, causing more than $100 billion in damages and over 2000 deaths.

Hurricane Katrina, the sixth-strongest Atlantic hurricane ever recorded, was the costliest and one of the deadliest hurricanes in U.S. history. Katrina formed over the Bahamas on August 23 and crossed southern Florida as a moderate Category 1 hurricane before passing over the warm Loop Current and strengthening rapidly in the Gulf of Mexico, causing it to become one of the strongest hurricanes ever recorded in the Gulf. The storm weakened considerably before making its second landfall as a Category 3 storm on the morning of August 29 in southeast Louisiana (Figure 6B). Still, Katrina was the largest hurricane of its strength to make landfall in the United States in recorded history; its sheer size caused devastation over a

FIGURE 6B Hurricane Katrina, the most destructive hurricane in U.S. history. Satellite view of Hurricane Katrina (*top*) coming ashore along the Gulf Coast on August 29, 2005. Hurricane Katrina, the largest hurricane of its strength to make landfall in the United States in recorded history, had a diameter of about 670 kilometers (415 miles); its counterclockwise direction of flow and prominent central eye are also visible. Katrina caused levees to breach and flooded New Orleans (*bottom*), which caused damages of more than $75 billion and claimed at least 1600 lives.

radius of 370 kilometers (230 miles). Katrina's 9-meter (30-foot) storm surge—the highest ever recorded in the United States—caused severe damage along the coasts of Mississippi, Louisiana, and Alabama.

Worse yet, Katrina was on a collision course with New Orleans. This scenario was considered a potential catastrophe because nearly all of the New Orleans metropolitan area is below sea level along Lake Pontchartrain. Even without a direct hit, the storm surge from Katrina was forecast to be greater than the height of the levees protecting New Orleans. This risk of devastation was well known; several previous studies warned that a direct hurricane strike on New Orleans could lead to massive flooding, which would lead to thousands of drowning deaths, as well as many more suffering from disease and dehydration after the hurricane passed. Although Katrina passed to the east of New Orleans, levees separating Lake Pontchartrain from New Orleans were breached by Katrina's high winds, storm surge, and heavy rains, ultimately flooding roughly 80% of the city and many neighboring areas (Figure 6B). Damages from Katrina are estimated to have been $75 billion, easily making it the costliest hurricane in U.S. history. The storm also left hundreds of thousands homeless and killed at least 1600 people, making it the deadliest U.S. hurricane since the 1928 Okeechobee Hurricane. The lack of adequate disaster response by the Federal Emergency Management Agency (FEMA) led to a U.S. Senate investigation in 2006 that recommended disbanding the agency and creating a new National Preparedness and Response Agency.

Hurricane Rita set records as the fourth most intense Atlantic hurricane ever recorded and the most intense tropical cyclone observed in the Gulf of Mexico, breaking the record set by Katrina just three weeks earlier. Rita reached its maximum intensity on September 21, with sustained winds of 290 kilometers (180 miles) per hour and an estimated minimum pressure of 89,500 Pascal (895 millibars, or 0.884 atmosphere). Hurricane Rita's unusually rapid intensification in the Gulf can likely be attributed to its passage over the warm Loop Current as well as higher-than-normal sea surface temperatures in the Gulf. Rita made landfall on September 24 near the Texas-Louisiana border as a Category 3 hurricane. Rita's 6-meter (20-foot) storm surge caused extensive damage along the coasts of Louisiana and extreme southeastern Texas, completely destroying some coastal communities and causing $10 billion in damage.

Later during the same season, Hurricane Wilma set numerous records for both strength and seasonal activity. Wilma was only the third Category 5 ever to develop during the month of October, and its pressure of 88,200 Pascal (882 millibars, or 0.871 atmosphere) ranked it as the most intense hurricane ever recorded in the Atlantic basin. Its maximum sustained near-surface wind speed reached 282 kilometers (175 miles) per hour, with gusts up to 320 kilometers (200 miles) per hour. Wilma made several landfalls, with the most destructive effects felt in the Yucatán Peninsula of Mexico, Cuba, and southern Florida. At least 62 deaths were reported, and damage was estimated at $16 to 20 billion ($12.2 billion in the United States), ranking Wilma among the top 10 costliest hurricanes ever recorded in the Atlantic and the sixth costliest storm in U.S. history. Wilma also affected 11 countries with winds or rainfall, more than any other hurricane in recent history.

sand called a barrier island located in the Gulf of Mexico off Texas (Figure 6.20). In 1900, it was a popular beach resort that averaged only 1.5 meters (5 feet) above sea level. At least 6000 people in and around Galveston were killed when the hurricane's 6-meter (20-foot)-high storm surge completely submerged the island, accompanied by heavy rainfall and winds of 160 kilometers (100 miles) per hour.

Category 4 hurricanes like the one in 1900 that made landfall in Galveston have been surpassed by Category 5 hurricanes only three times in the United States: (1) in 1935, an unnamed hurricane[10] flattened the Florida Keys; (2) in 1969, Hurricane Camille struck Mississippi; and (3) in 1992, Hurricane Andrew came ashore in southern Florida, with winds as high as 258 kilometers (160 miles) per hour, ripping down every tree in its path as it crossed the Everglades. Hurricane Andrew did more than $26.5 billion of damage in Florida and along the Gulf Coast. In the aftermath of Hurricane Andrew, more than 250,000 people were left homeless and although most people heeded the warnings to evacuate, 54 were killed.

In October 1998, Hurricane Mitch proved to be one of the most devastating tropical cyclones to affect the Western Hemisphere. At its peak, it was estimated to have winds of 290 kilometers (180 miles) per hour—a strong Category 5 hurricane.

WEB VIDEO

Hurricane Katrina Damage

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[10] Prior to 1950, Atlantic hurricanes were not named, but this hurricane is often referred to as the "Labor Day Hurricane" because it came ashore then. Today, hurricanes are named by forecasters using an alphabetized list of female and male names.

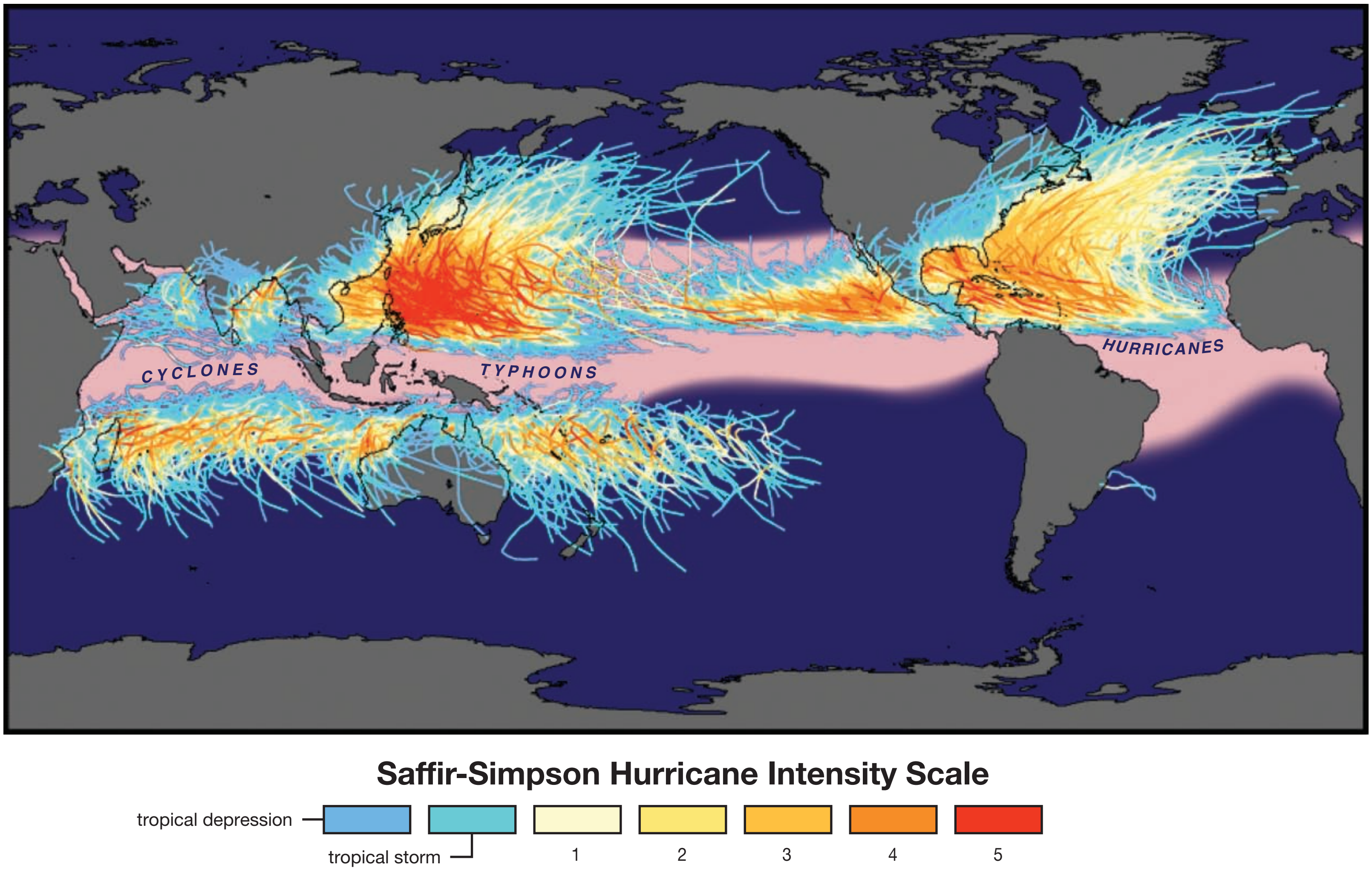


FIGURE 6.17 Historic tropical cyclone tracks. Color-coded map showing the intensity and paths of tropical cyclones (which, depending on the area, can also be called *hurricanes* or *typhoons*) over the past 150 years. Cyclones originate in low-latitude regions that have warm ocean surface temperatures (*red shading*). Once formed, cyclones are influenced by the trade winds, so generally travel from east to west. Note that cyclones curve to the right north of the equator and to the left south of the equator because of the Coriolis effect, which causes cyclones to track away from the tropics into cooler water or land (and sometimes into the middle latitudes), where they die out.

It hit Central America with winds of 160 kilometers (100 miles) per hour and as much as 130 centimeters (51 inches) of total rainfall, causing widespread flooding and mudslides in Honduras and Nicaragua that destroyed entire towns. The hurricane resulted in more than 11,000 deaths, left more than 2 million homeless, and caused more than $10 billion in damage across the region.

In September 2008, Hurricane Ike reached Category 4 in the Gulf of Mexico and made landfall near Galveston in low-lying Gilchrist, Texas, as a Category 2 hurricane. Ike resulted in 146 deaths and $24 billion in damages (Figure 6.21), making it the third costliest U.S. hurricane of all time, behind only Hurricane Katrina (2005) and Hurricane Andrew (1992).

The majority of the world's tropical cyclones are formed in the waters north of the equator in the western Pacific Ocean. These storms, called typhoons, do enormous damage to coastal areas and islands in Southeast Asia (see Figure 6.17).

Other areas of the world such as Bangladesh experience tropical cyclones on a regular basis. Bangladesh borders the Indian Ocean and is particularly vulnerable because it is a highly populated and low-lying country, much of it only 3 meters (10 feet) above sea level. In 1970, a 12-meter (40-foot)-high storm surge from a tropical cyclone killed an estimated 1 million people. Another tropical cyclone

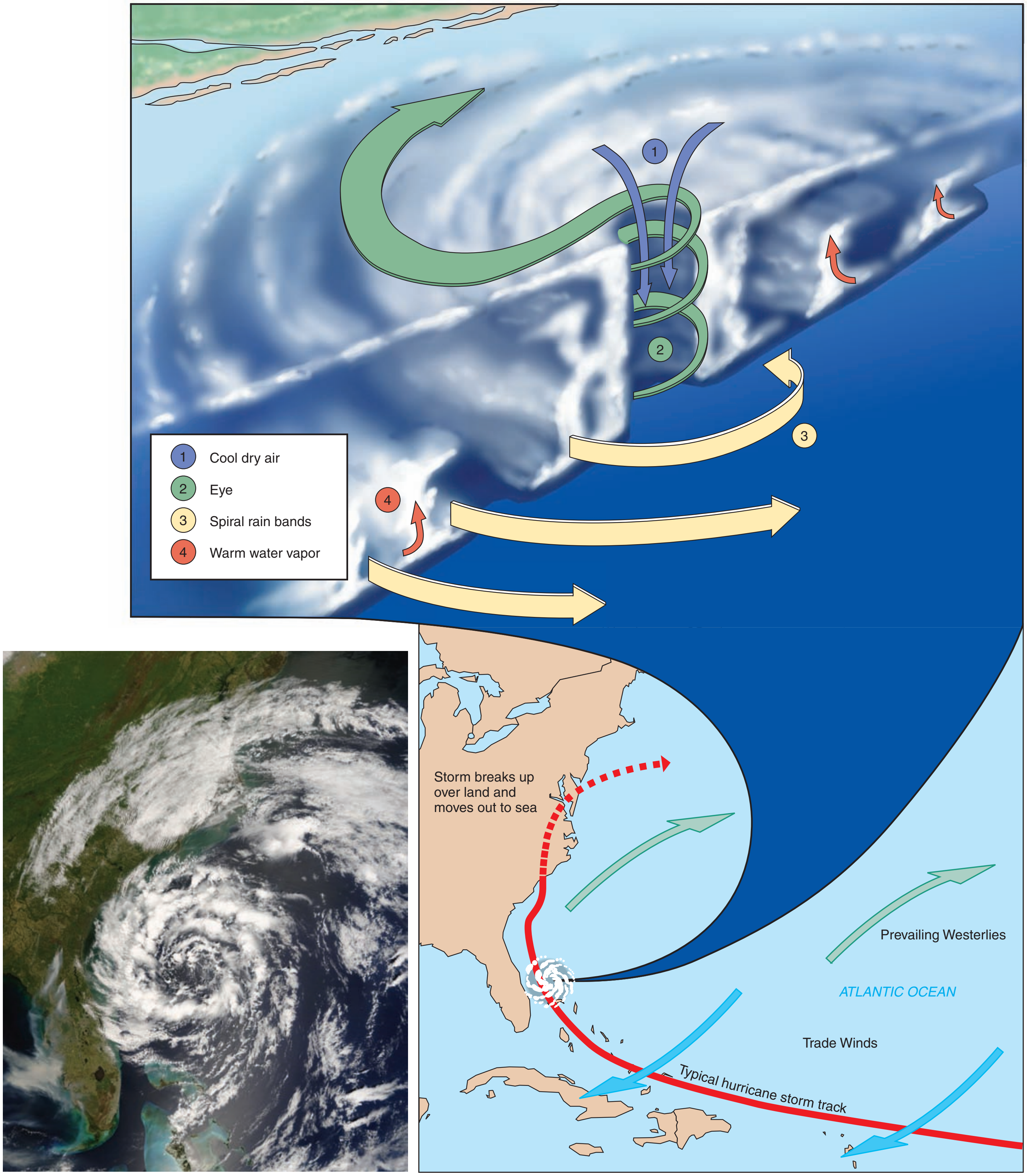
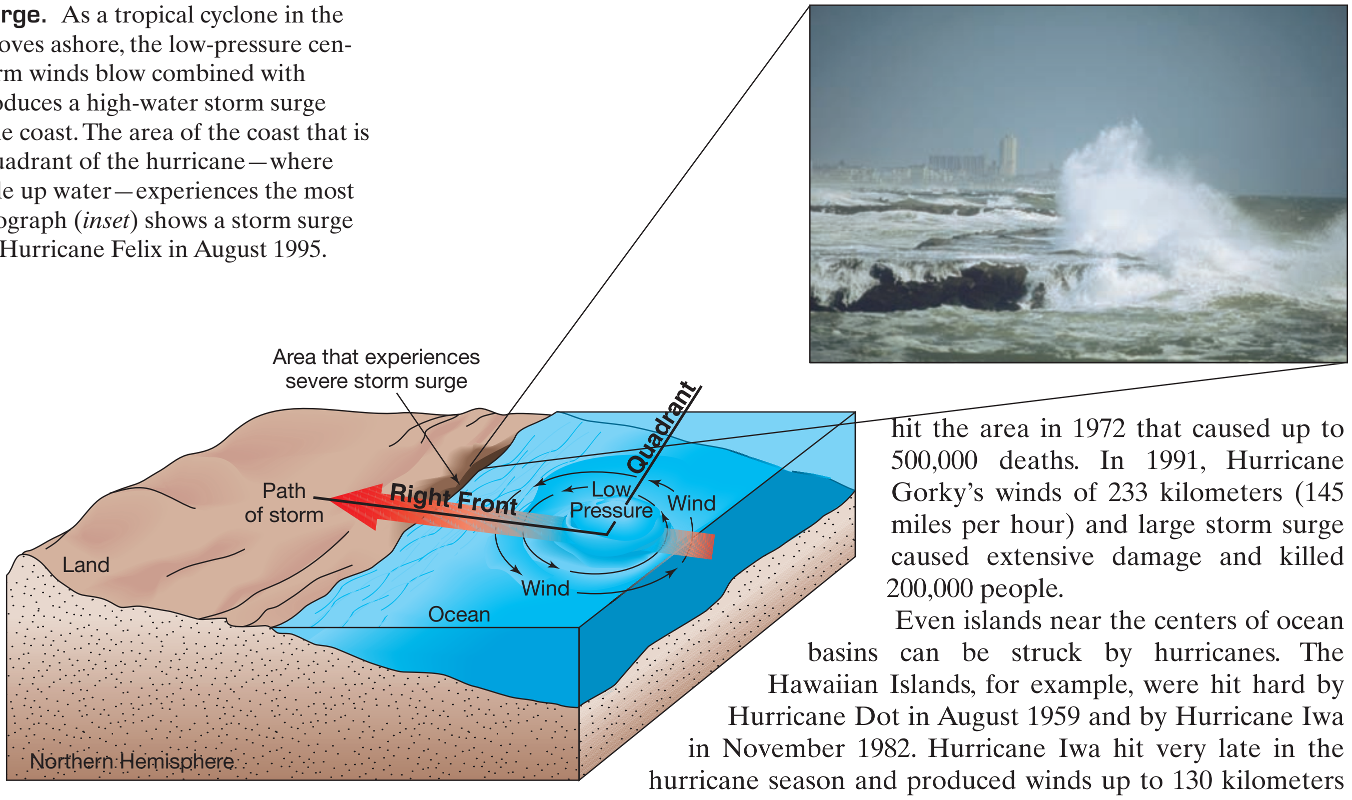


FIGURE 6.18 Typical North Atlantic hurricane storm track and internal structure. Hurricanes in the North Atlantic are blown by the trade winds towards North America. As they curve to the right because of the Coriolis effect, they move northward and often make landfall or pass close to shore. Eventually, they break up and are transported out to sea by the prevailing westerlies. Photo shows subtropical storm Andrea off the East Coast in 2007; internal structure of a hurricane is also shown (*enlargement*).

FIGURE 6.19 Storm surge. As a tropical cyclone in the Northern Hemisphere moves ashore, the low-pressure center around which the storm winds blow combined with strong onshore winds produces a high-water storm surge that floods and batters the coast. The area of the coast that is hit with the right front quadrant of the hurricane—where onshore winds further pile up water—experiences the most severe storm surge. Photograph (*inset*) shows a storm surge in New Jersey caused by Hurricane Felix in August 1995.



hit the area in 1972 that caused up to 500,000 deaths. In 1991, Hurricane Gorky's winds of 233 kilometers (145 miles per hour) and large storm surge caused extensive damage and killed 200,000 people.

Even islands near the centers of ocean basins can be struck by hurricanes. The Hawaiian Islands, for example, were hit hard by Hurricane Dot in August 1959 and by Hurricane Iwa in November 1982. Hurricane Iwa hit very late in the hurricane season and produced winds up to 130 kilometers (81 miles) per hour. Damage of more than $100 million occurred on the islands of Kauai and Oahu. Niihau, a small island that is inhabited by 230 native Hawaiians, was directly in the path of the storm and suffered severe property damage but no serious injuries. Hurricane Iniki roared across the islands of Kauai and Niihau in September 1992, with 210-kilometer (130-mile)-per-hour winds. It was the most powerful hurricane to hit the Hawaiian Islands in the last 100 years, with property damage that approached $1 billion.

Hurricanes will continue to be a threat to life and property. Because of more accurate forecasts and prompt evacuation, however, the loss of life has been decreasing. Property damage, on the other hand, has been increasing because increasing coastal populations have resulted in more and more construction along the coast. Inhabitants of areas subject to a hurricane's destructive force must be made aware of the danger so that they can be prepared for its eventuality.

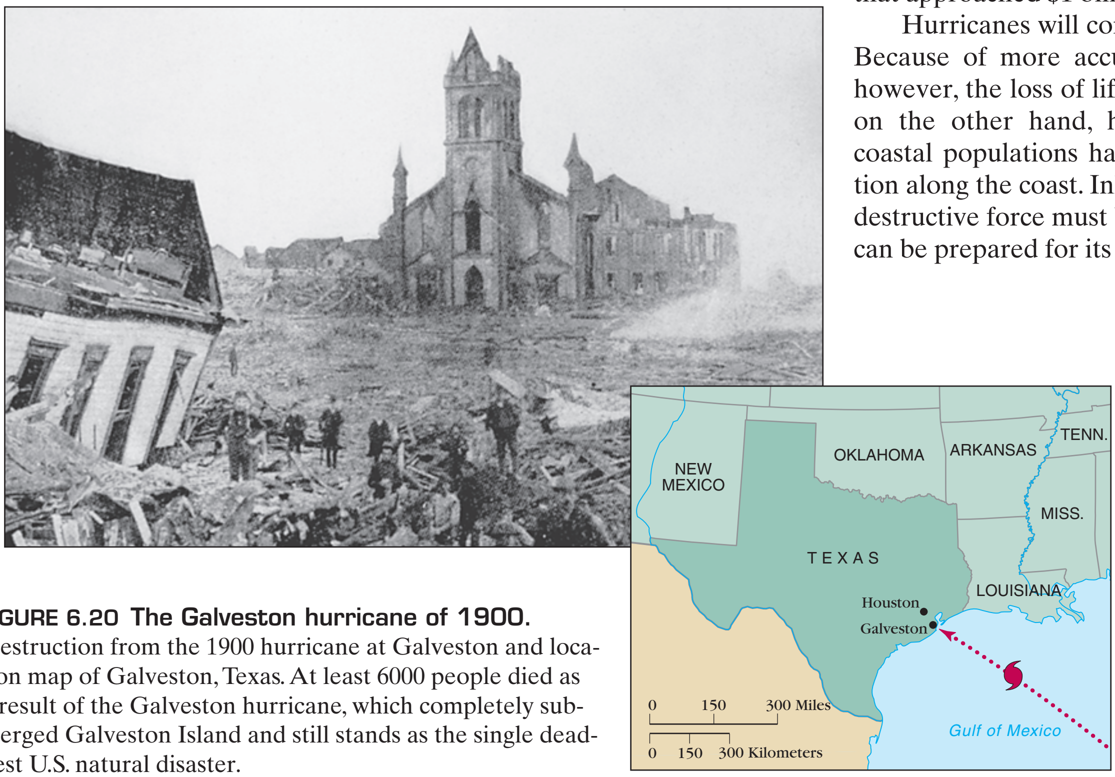


FIGURE 6.20 The Galveston hurricane of 1900. Destruction from the 1900 hurricane at Galveston and location map of Galveston, Texas. At least 6000 people died as a result of the Galveston hurricane, which completely submerged Galveston Island and still stands as the single deadliest U.S. natural disaster.

The Ocean's Climate Patterns

Just as land areas have climate patterns, so do regions of the oceans. The open ocean is divided into climatic regions that run generally east–west (parallel to lines of latitude) and have relatively stable boundaries that are somewhat modified by ocean surface currents (Figure 6.22).

The **equatorial** region spans the equator, which gets an abundance of solar radiation. As a result, the major air movement is upward because heated air rises. Surface winds, therefore, are weak and variable, which is why this region is called the *doldrums*. Surface waters are warm and the air is saturated with water vapor. Daily rain showers are common, which keeps surface salinity relatively low. The equatorial regions just north or south of the equator are also the breeding grounds for tropical cyclones.

Tropical regions extend north or south of the equatorial region up to the Tropic of Cancer and the Tropic of Capricorn, respectively. They are characterized by strong trade winds, which blow from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. These winds push the equatorial currents and create moderately rough seas. Relatively little precipitation falls at higher latitudes within tropical regions, but precipitation increases toward the equator. Once tropical cyclones form, they gain energy here as large quantities of heat are transferred from the ocean to the atmosphere.

Beyond the tropics are the **subtropical** regions. Belts of high pressure are centered there, so the dry, descending air produces little precipitation and a high rate of evaporation, resulting in the highest surface salinities in the open ocean (see Figure 5.23). Winds are weak and currents are sluggish, typical of the horse latitudes. However, strong boundary currents (along the boundaries of continents) flow north and south, particularly along the western margins of the subtropical oceans.

The **temperate** regions (also called the *middle latitudes* or *midlatitudes*) are characterized by strong westerly winds (the prevailing westerlies) blowing from the southwest in the Northern Hemisphere and from the northwest in the Southern Hemisphere (see Figure 6.11). Severe storms are common, especially during winter, and precipitation is heavy. In fact, the North Atlantic is noted for fierce storms, which have claimed many ships and numerous lives over the centuries.

The **subpolar** region experiences extensive precipitation due to the subpolar low. Sea ice covers the subpolar ocean in winter, but it melts away, for the most part, in summer. Icebergs are common, and the surface temperature seldom exceeds 5°C (41°F) in the summer months.

Surface temperatures remain at or near freezing in the **polar** regions, which are covered with ice throughout most of the year. The polar high pressure dominates the area, which includes the Arctic Ocean and the ocean adjacent to Antarctica. There is no sunlight during the winter and constant daylight during the summer.

FIGURE 6.21 Damage from Hurricane Ike in 2008. Hurricane Ike, which made landfall in Gilchrist, Texas, was the third most destructive hurricane to ever make landfall in the United States.

KEY CONCEPT
Hurricanes are intense and sometimes destructive tropical storms that form where water temperatures are high, where there is an abundance of warm moist air, and where they can spin.

6.7 How Do Sea Ice and Icebergs Form?

Low temperatures in high-latitude regions cause a permanent or nearly permanent ice cover on the sea surface. The term **sea ice** is used to distinguish such masses of frozen seawater from **icebergs**, which are also found at sea but originate by breaking off (*calving*) from glaciers that originate on land. Sea ice is found throughout the year around the margin of Antarctica, within the Arctic Ocean, and in the extreme high-latitude region of the North Atlantic Ocean.

Formation of Sea Ice

Sea ice is ice that forms directly from seawater (Figure 6.23). It begins as small, needle-like, hexagonal (six-sided) crystals, which eventually become so numerous that a *slush* develops. As the slush begins to form into a thin sheet, it is broken by wind stress and wave action into disk-shaped pieces called **pancake ice** (Figure 6.23a). As further freezing occurs, the pancakes coalesce to form **ice floes** (*flo* = layer).

The rate at which sea ice forms is closely tied to temperature conditions. Large quantities of ice form in relatively short periods when the temperature falls

FIGURE 6.22 The ocean's climatic regions. The ocean's climatic regions are defined primarily by latitude but are modified by ocean currents and wind belts. Red arrows indicate warm surface currents; blue arrows indicate cool surface currents.

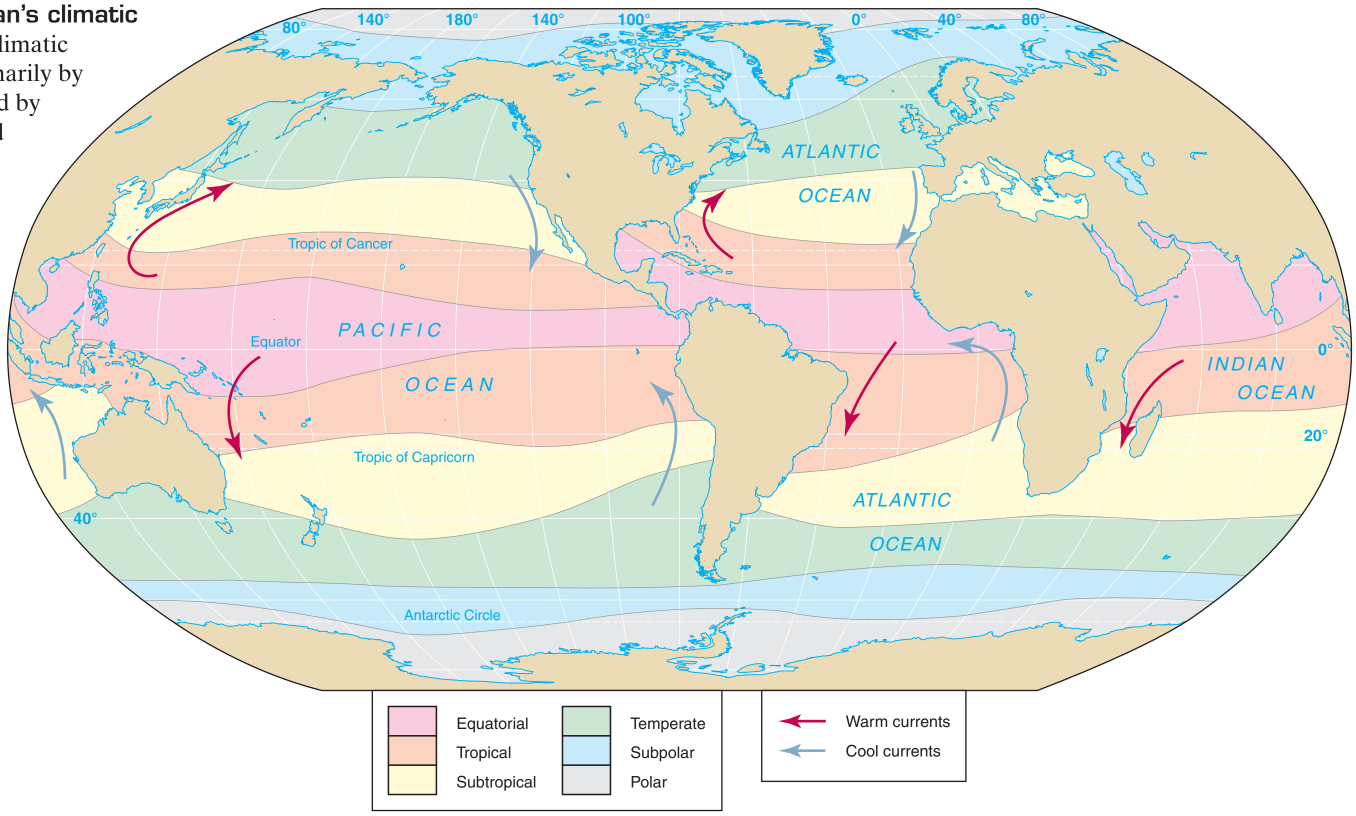
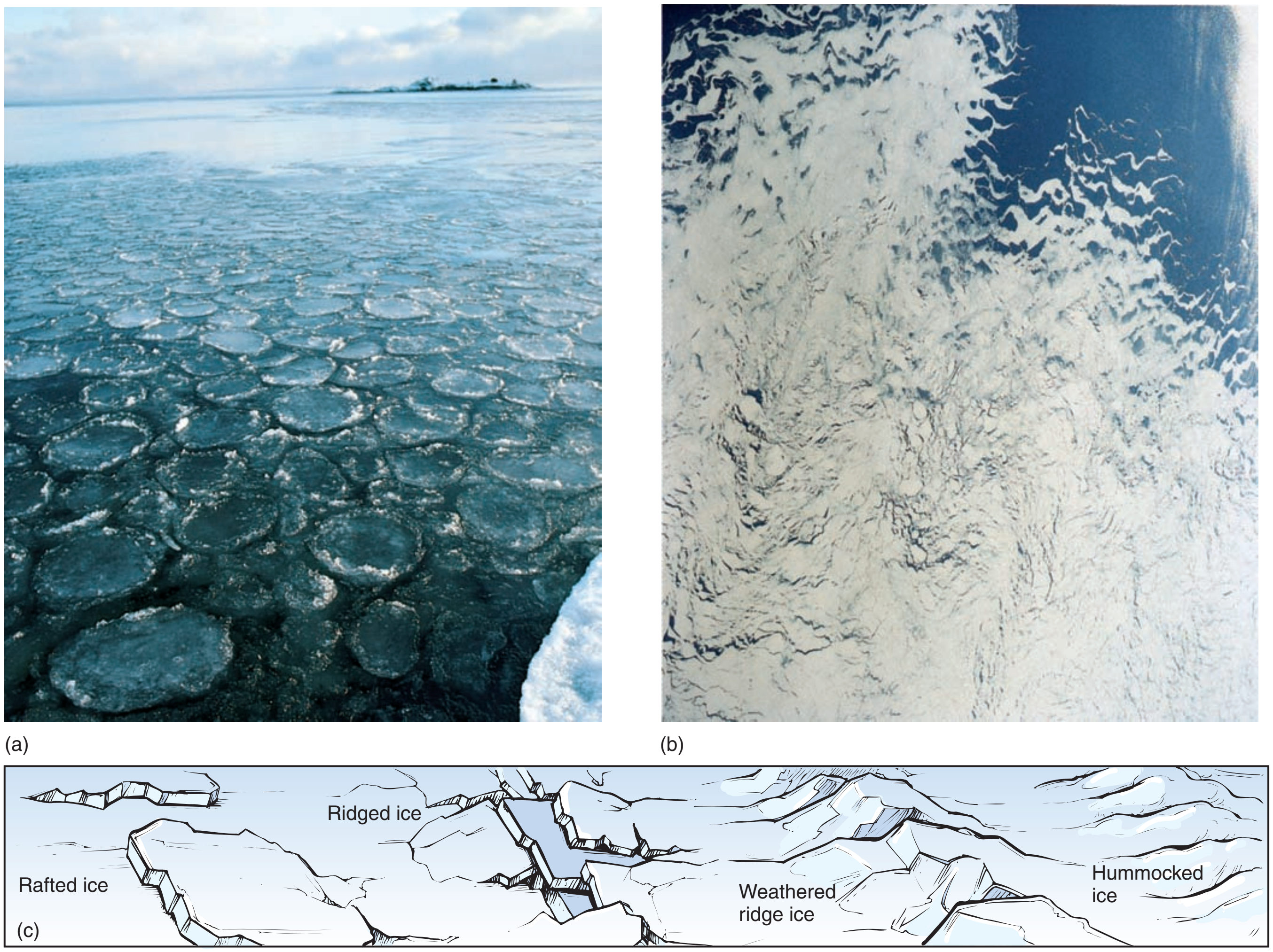


FIGURE 6.23 Sea ice. **(a)** Pancake ice, which is frozen slush that is broken by wind stress and wave action into disk-shaped pieces. **(b)** Aerial view of the Larsen ice shelf on the Antarctic Peninsula, where ribbons of sea ice (*top*) remain seaward of the shelf ice during September (the beginning of the spring season in the Southern Hemisphere). **(c)** Ice structures associated with rafted ice, which is created as ice floes expand and raft onto one another.



to extremely low levels [such as temperatures below −30°C (−22°F)]. Even at these low temperatures, the rate of ice formation slows as sea ice thickens because the ice (which has poor heat conduction) effectively insulates the underlying water from freezing. In addition, calm water enables pancake ice to join together more easily, which aids the formation of sea ice.

The process of sea ice formation tends to be a self-perpetuating process. As sea ice forms at the surface, only a small percentage of the dissolved components can be accommodated into the crystalline structure of ice. As a result, most of the dissolved substances remain in the surrounding seawater, which causes its salinity to increase. Recall from Chapter 5 that increasing the amount of dissolved materials

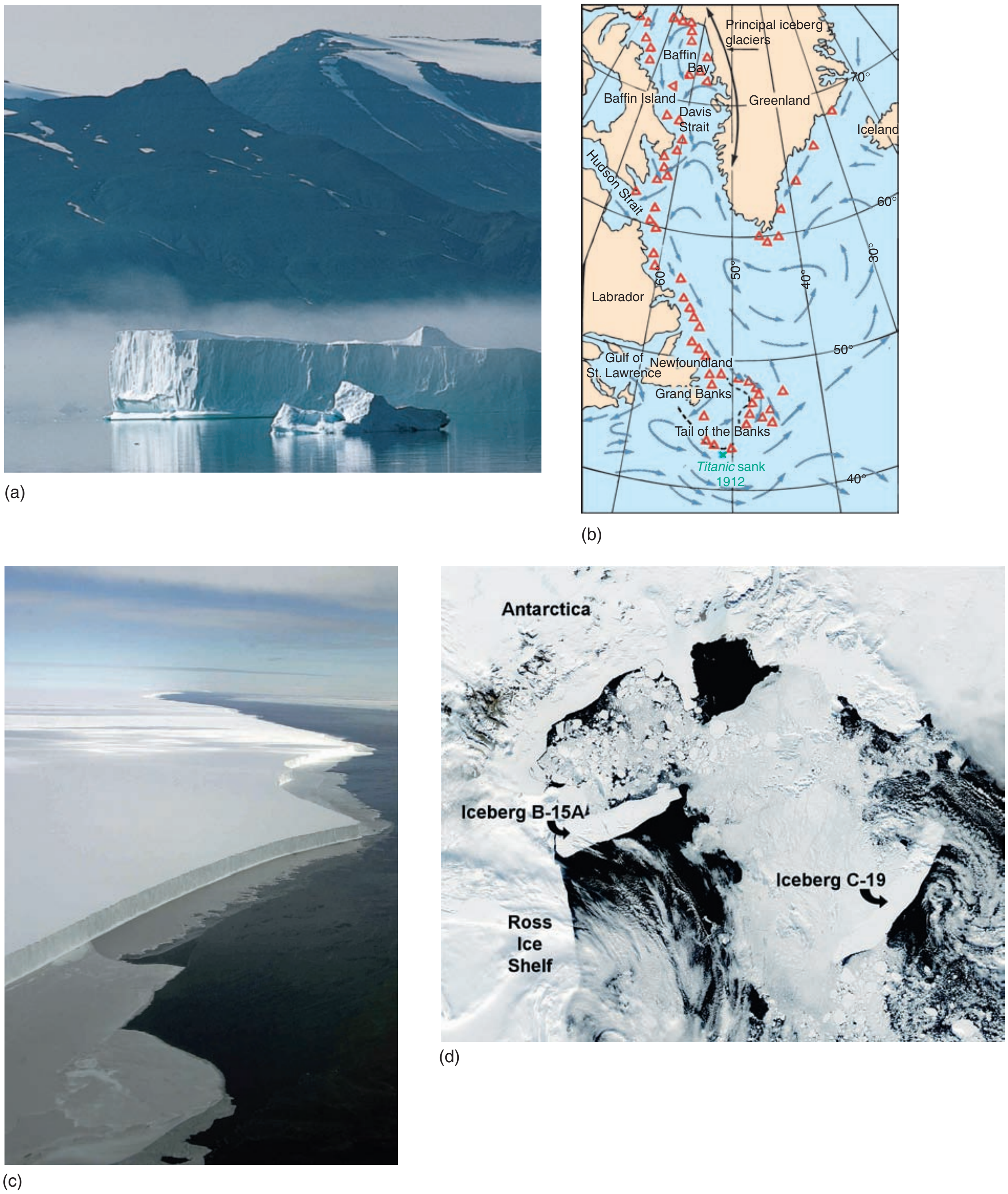


FIGURE 6.24 Icebergs. **(a)** Icebergs, such as this small North Atlantic berg, are formed when pieces of ice calve from glaciers that reach the sea. **(b)** Map showing North Atlantic currents (*blue arrows*), typical iceberg distribution (*red triangles*), and site of the 1912 *Titanic* disaster (*green X*). **(c)** Part of a large tabular Antarctic iceberg. **(d)** Satellite view of iceberg C-19, which broke off from Antarctica's Ross Ice Shelf in May 2002. Also shown is iceberg B-15A, which is part of the larger B-15 iceberg that was the size of Connecticut when it calved in March 2000.

decreases the freezing point of water, which doesn't appear to enhance ice formation. However, also recall that increasing the salinity of water increases its density and its tendency to sink. As it sinks below the surface, it is replaced by lower-salinity (and lower-density) water from below, which will freeze more readily than the high salinity water it replaced, thereby establishing a circulation pattern that enhances the formation of sea ice.

Recent satellite analyses of the extent of Arctic Ocean sea ice shows that it has decreased dramatically in the past few decades. This accelerated melting appears to be linked to shifts in Northern Hemisphere atmospheric circulation patterns that have caused the region to experience anomalous warming. For more on this topic, see Chapter 16, "The Oceans and Climate Change."

Formation of Icebergs

Icebergs are bodies of floating ice broken away from a glacier (Figure 6.24a) and so are quite distinct from sea ice. Icebergs are formed by vast ice sheets on land, which grow from the accumulation of snow and slowly flow outward to the sea. Once at the sea, the ice either breaks up and produces icebergs there, or, because it is less dense than water, it floats on top of the water, often extending a great distance away from shore before breaking up under the stress of current, wind, and wave action. Most calving occurs during the summer months when temperatures are highest.

In the Arctic, icebergs originate primarily by calving from glaciers that extend to the ocean along the western coast of Greenland (Figure 6.24b). Icebergs are also produced by glaciers along the eastern coasts of Greenland, Ellesmere Island, and other Arctic islands. In all, about 10,000 or so icebergs are calved off these glaciers each year. Many of these icebergs are carried by the East Greenland Current and the West Greenland Current (Figure 6.24b, *arrows*) into North Atlantic shipping lanes, where they become navigational hazards. In recognition of this fact, the area is called Iceberg Alley; it is here that the luxury liner RMS *Titanic* hit an iceberg and sank (see Web Box 6.1). Because of their large size, some of these icebergs take several years to melt, and, in that time, they may be carried as far south as 40 degrees north latitude, which is the same latitude as Philadelphia.

SHELF ICE In Antarctica, where glaciers cover nearly the entire continent, the edges of glaciers form thick floating sheets of ice called **shelf ice** that break off and produce vast plate-like icebergs (Figures 6.24c and 6.24d). In March 2000, for example, a Connecticut-sized iceberg (11,000 square kilometers or 4250 square miles) known as B-15 and nicknamed "Godzilla" broke loose from the Ross Ice Shelf into the Ross Sea. By comparison, the largest iceberg ever recorded in Antarctic waters was nearly three times the size of B-15 and measured an incredible 335 by 97 kilometers (208 by 60 miles)—about the same size as Connecticut and Massachusetts combined.

The icebergs have flat tops that may stand as much as 200 meters (650 feet) above the ocean surface, although most rise less than 100 meters (330 feet) above sea level, and as much as 90% of their mass is below waterline. Once icebergs are created, ocean currents driven by strong winds carry the icebergs north, where they eventually melt. Because this region is not a major shipping route, the icebergs pose little serious navigation hazard except for supply ships traveling to Antarctica. Officers aboard ships sighting these gigantic bergs have, in some cases, mistaken them for land!

The rate at which Antarctica is producing icebergs—especially large icebergs—has recently increased, most likely as a result of Antarctic warming. For more information about Antarctic warming and its relationship to climate change, see Chapter 16, "The Oceans and Climate Change."

KEY CONCEPT

Sea ice is created when seawater freezes; icebergs form when chunks of ice break off from coastal glaciers that reach the sea.

6.8 Can Power from Wind Be Harnessed as a Source of Energy?

The uneven heating of Earth by the Sun drives various small- and large-scale winds. These winds, in turn, can be harnessed to turn windmills or turbines that generate electricity. At various places on land where the wind blows constantly, wind farms have been constructed that consist of hundreds of large turbines mounted on tall towers, thereby taking advantage of this renewable, clean energy source. Similar facilities could be built offshore, where the wind generally blows harder and more steadily than on land. Figure 6.25 shows the offshore areas where the potential for wind farms exist.

Some offshore wind farms have already been built and many more are in the planning stage. In the North Sea north of windswept northern Europe, for example, about 100 sea-based turbines are already operating (Figure 6.26), with hundreds more planned. In fact, Denmark generates 18% of its power by wind—more than any other country—and hopes to increase its proportion of wind power to 50% by 2030. In the United States, America's first offshore wind farm, Cape Wind, is scheduled to be built on Horseshoe Shoal in Nantucket Sound, Massachusetts, 8 kilometers (5 miles) south of Cape Cod. The wind farm expects to be fully functional in 2011 with 130 wind turbines capable of producing 420 megawatts of power, which is capable of supplying the energy needs of nearly 350,000 average U.S. homes.

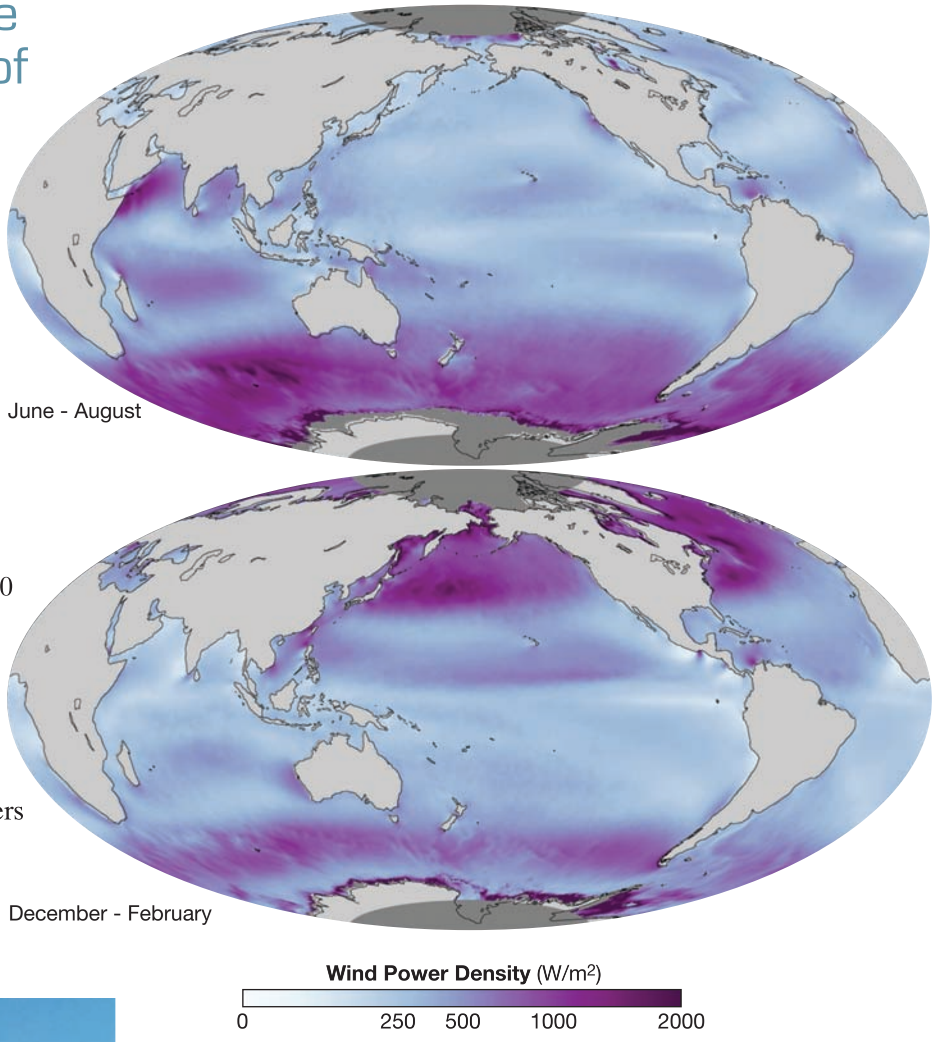


FIGURE 6.25 Global ocean wind energy potential. Average ocean wind intensity maps during 2000–2007 for June–August (*top*) and December–February (*bottom*). Areas of high wind power density, where winds are strongest and the potential for wind farms is greatest, are shown in purple, while low power density regions where winds are light are shown in light blue and white.

FIGURE 6.26 Offshore wind farm. Offshore wind turbines form a part of a wind farm in the North Sea off the coast of Blyth in the U.K.

Chapter in Review

- *The atmosphere and the ocean act as one interdependent system*, linked by complex feedback loops. There is a close association between most atmospheric and oceanic phenomena.
- *The Sun heats Earth's surface unevenly due to the change of seasons* (*caused by the tilt of Earth's rotational axis*, which is 23.5 degrees from vertical) and the daily cycle of sunlight and darkness (Earth's rotation on its axis). The *uneven distribution of solar energy on Earth* influences most of the physical properties of the atmosphere (such as *temperature, density, water vapor content*, and *pressure differences*) that produce *atmospheric movement*.
- *The Coriolis effect influences the paths of moving objects on Earth and is caused by Earth's rotation*. Because Earth's surface rotates at different velocities at different latitudes, *objects in motion tend to veer to the right in the Northern Hemisphere and to the left in the Southern Hemisphere*. The Coriolis effect is *nonexistent at the equator but increases with latitude*, reaching a maximum at the poles.
- *More solar energy is received than is radiated back into space at low latitudes than at high latitudes*. On the spinning Earth, this creates *three circulation cells in each hemisphere*: a *Hadley cell* between 0 and 30 degrees latitude, a *Ferrel cell* between 30 and 60 degrees latitude, and a *polar cell* between 60 and 90 degrees latitude. High-pressure regions, where dense air descends, are located at about 30 degrees north or south latitude and at the poles. Belts of low pressure, where air rises, are generally found at the equator and at about 60 degrees latitude.
- *The movement of air within the circulation cells produces the major wind belts of the world*. The air at Earth's surface that is moving away from the subtropical highs produces *trade winds* moving toward the equator and *prevailing westerlies* moving toward higher latitudes. The air moving along Earth's surface from the polar high to the subpolar low creates the *polar easterlies*.
- *Calm winds characterize the boundaries between the major wind belts of the world*. The boundary between the two trade wind belts is called the *doldrums*, which coincides with the Intertropical Convergence Zone (ITCZ). The boundary between the trade winds and the prevailing westerlies is called the *horse latitudes*. The boundary between the prevailing westerlies and the polar easterlies is called the *polar front*.
- The *tilt of Earth's axis of rotation*, the *lower heat capacity of rock material* compared to seawater, and the *distribution of continents modify the wind and pressure belts of the idealized three-cell model*. However, the three-cell model closely matches the pattern of the major wind belts of the world.
- *Weather describes the conditions of the atmosphere at a given place and time, while climate is the long-term average of weather*. Atmospheric motion (*wind*) *is always from high-pressure regions toward low-pressure regions*. In the Northern Hemisphere, therefore, there is a *counterclockwise cyclonic movement* of air around low-pressure cells and a *clockwise anticyclonic movement* around high-pressure cells. Coastal regions commonly experience *sea and land breezes*, due to the daily cycle of heating and cooling.
- *Many storms are due to the movement of air masses*. In the middle latitudes, cold air masses from higher latitudes meet warm air masses from lower latitudes and create *cold and warm fronts* that move from west to east across Earth's surface. *Tropical cyclones (hurricanes) are large, powerful storms that mostly affect tropical regions of the world*. Destruction caused by hurricanes is caused by storm surge, high winds, and intense rainfall.
- *The ocean's climate patterns are closely related to the distribution of solar energy and the wind belts of the world*. Ocean surface currents somewhat modify oceanic climate patterns.
- *In high latitudes, low temperatures freeze seawater and produce sea ice*, which forms as a slush and breaks into pancakes that ultimately grow into ice floes. *Icebergs form when chunks of ice break off glaciers* that form on Antarctica, Greenland, and some Arctic islands. Floating sheets of ice called *shelf ice* near Antarctica produce the largest icebergs.
- *Winds can be harnessed as a source of power*. There is vast potential for developing this clean, renewable resource and several offshore wind farm systems currently exist.

Key Terms

Air mass (p. 176)
Albedo (p. 163)
Antarctic Circle (p. 163)
Anticyclonic flow (p. 174)
Arctic Circle (p. 163)
Autumnal equinox (p. 162)
Climate (p. 174)
Cold front (p. 176)
Columbus, Christopher (p. 175)
Convection cell (p. 165)
Coriolis effect (p. 167)
Cyclone (p. 177)
Cyclonic flow (p. 174)
Declination (p. 162)
Doldrums (p. 172)
Ecliptic (p. 161)
Equatorial (p. 184)
Equatorial low (p. 171)
Eye of the hurricane (p. 179)
Ferrel cell (p. 170)
Hadley cell (p. 170)
Horse latitudes (p. 172)
Hurricane (p. 177)
Ice floe (p. 185)
Icebergs (p. 185)
Intertropical Convergence Zone (ITCZ) (p. 172)
Jet stream (p. 176)
Land breeze (p. 176)
Northeast trade winds (p. 172)
Pancake ice (p. 185)
Polar (p. 185)
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Review Questions

1. Sketch a labeled diagram to explain the cause of Earth's seasons.

2. Along the Arctic Circle, how would the Sun appear during the summer solstice? During the winter solstice?

3. If there is a net annual heat loss at high latitudes and a net annual heat gain at low latitudes, why does the temperature difference between these regions not increase?

4. Describe the physical properties of the atmosphere, including its composition, temperature, density, water vapor content, pressure, and movement.

5. Is Earth's atmosphere heated from above or below? Explain.

6. Describe the Coriolis effect in the Northern and Southern Hemispheres and include a discussion of why the strength of the Coriolis effect increases at higher latitudes.

7. Sketch the pattern of surface wind belts on Earth, showing atmospheric circulation cells, zones of high and low pressure, the names of the wind belts, and the names of the boundaries between the wind belts.

8. Why are there high-pressure caps at each pole and a low-pressure belt in the equatorial region?

9. Describe the difference between cyclonic and anticyclonic flow, and show how the Coriolis effect is important in producing both a clockwise and a counterclockwise flow pattern.

10. How do sea breezes and land breezes form? During a hot summer day, which one would be most common and why?

11. Name the polar and tropical air masses that affect U.S. weather. Describe the pattern of movement across the continent and patterns of precipitation associated with warm and cold fronts.

12. What are the conditions needed for the formation of a tropical cyclone? Why do most middle latitude areas only rarely experience a hurricane? Why are there no hurricanes at the equator?

13. Describe the types of destruction caused by hurricanes. Of those, which one causes the majority of fatalities and destruction?

14. How are the ocean's climatic regions (Figure 6.22) related to the broad patterns of air circulation described in Figure 6.11? What are some areas where the two are not closely related?

15. Describe differences between sea ice and icebergs, including how they both form.

Critical Thinking Exercises

1. Describe the effect on Earth as a result of Earth's axis of rotation being angled 23.5 degrees from perpendicular relative to the ecliptic. What would happen if Earth were not tilted on its axis?

2. Discuss why the idealized belts of high and low atmospheric pressure shown in Figure 6.11 are modified (see Figure 6.12).

3. What is the difference between weather and climate? If it rains in a particular area during a day, does that mean that the area has a wet climate? Explain.

Oceanography on the Web

Visit the *Essentials of Oceanography* Online Study Guide for Internet resources, including chapter-specific quizzes to test your understanding and Web links to further your exploration of the topics in this chapter.

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