Pearson New International Edition

Essentials of Oceanography

Alan P. Trujillo Harold V. Thurman

Eleventh Edition

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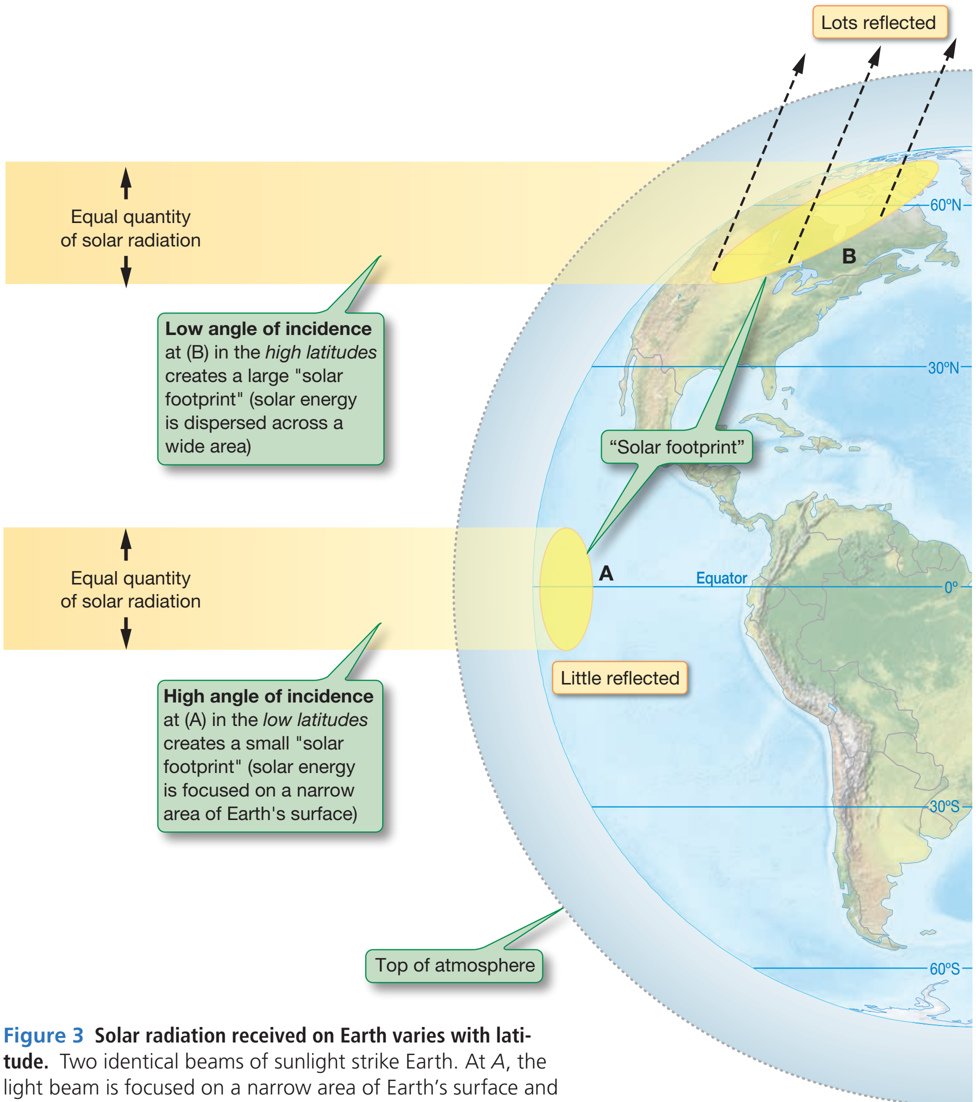

Figure 3 Solar radiation received on Earth varies with latitude. Two identical beams of sunlight strike Earth. At *A*, the light beam is focused on a narrow area of Earth's surface and produces a smaller "solar footprint"; at *B*, the light beam is dispersed across a wide area and produces a larger "solar 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.

- 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 1**). Thus, the ocean reflects more radiation at high latitudes than at low latitudes.

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

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. In addition, ice has a high albedo, so more energy is reflected back into space than is 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 is reflected

TABLE 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

[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.

back into space. The graph in **Figure 4** 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 4, 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.

ESSENTIAL CONCEPT 1B

Low-latitude regions receive more solar radiation than high-latitude regions, but oceanic and atmospheric circulation transfer heat around the globe.

CONCEPT CHECK 1

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?

2 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.

Composition Of the Atmosphere

Figure 5 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.

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*.

Figure 6 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

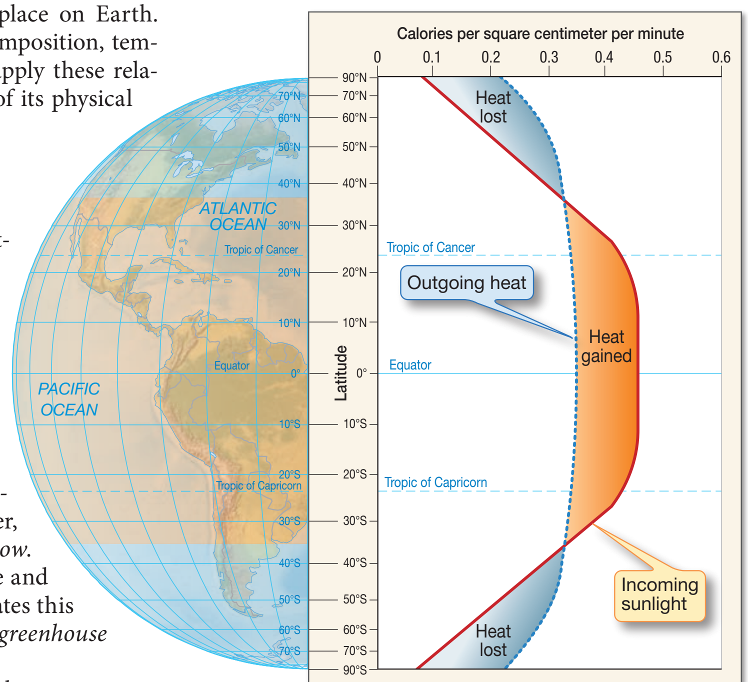

Figure 4 Heat gained and lost from the ocean varies with latitude. Heat gained by the oceans in equatorial latitudes (*orange shading*) equals heat lost in polar latitudes (*blue shading*). On average, the two balance each other, and the excess heat from equatorial latitudes is transferred to heat-deficient polar latitudes by both oceanic and atmospheric circulation.

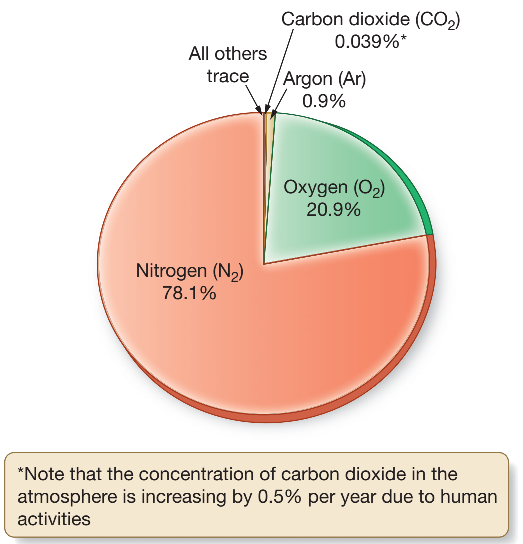

Figure 5 Composition of dry air. Pie chart showing the composition of dry air (without any water vapor) by volume. Nitrogen and oxygen gas comprise 99% of the total, with several trace gases making up the rest; the most significant trace gas is carbon dioxide, an important greenhouse gas.

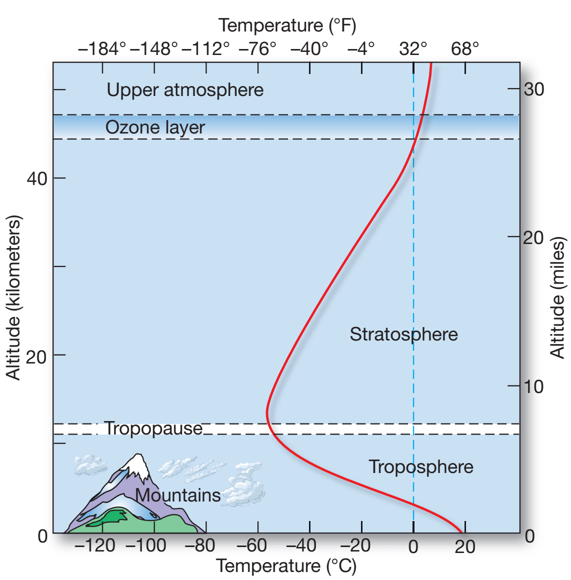

Figure 6 Temperature profile of the atmosphere. Within the troposphere, the atmosphere gets cooler with increasing altitude. Above the troposphere, the atmosphere generally warms.

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 7 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.

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.

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.

[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.

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 8, 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.

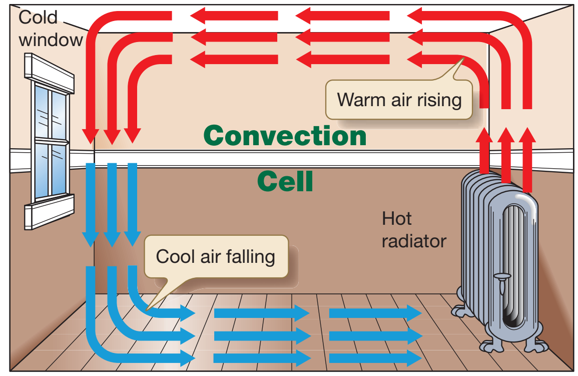

Figure 7 Convection in a room. A circular-moving loop of air (a convection cell) is caused by warm air rising and cool air sinking.

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 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 9). 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) 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, the poles experience high pressure and clear, dry weather.

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

STUDENTS SOMETIMES ASK . . .

Why is there so much nitrogen in the atmosphere?

To understand the abundance of nitrogen in the atmosphere, it's useful to compare it to oxygen, the next most abundant element in the atmosphere. Figure 5, for example, shows that nitrogen is about four times as abundant in the atmosphere as oxygen. However, if we consider the relative abundances of oxygen and nitrogen over the entire Earth, oxygen is about 10,000 times more abundant. These earthly abundances overall reflect the composition of the material from which Earth originally formed and the process of Earth's accretion. Oxygen is a major component of the solid Earth, along with silicon and elements such as magnesium, calcium, and sodium. Nitrogen is not stable as part of a crystal lattice, so it is not incorporated into the solid Earth. This is one reason why nitrogen is so enriched in the atmosphere relative to oxygen. The other primary reason is that, unlike oxygen, nitrogen is very stable in the atmosphere and is not involved to a great extent in chemical reactions that occur there. Thus, over geologic time, it has built up in the atmosphere to a much greater extent than oxygen.

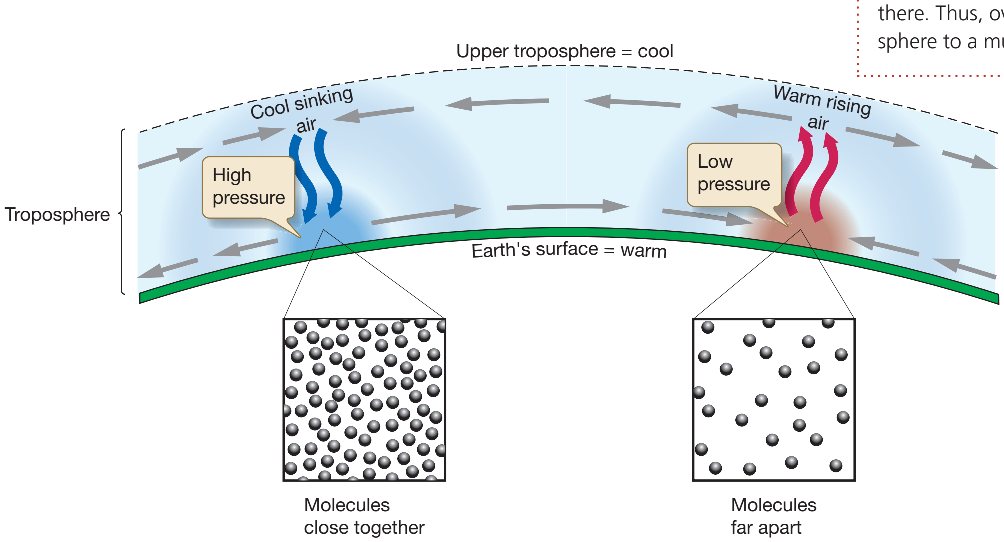

Figure 8 High and low atmospheric pressure zones. A column of cool, dense air causes high pressure at the surface (*left*), which will lead to sinking air. A column of warm, less dense air causes low pressure at the surface (*right*), which will lead to rising air.

ESSENTIAL CONCEPT 2

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

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 7).

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.

CONCEPT CHECK 2

1. Describe the physical properties of the atmosphere, including its composition, temperature, density, water vapor content, pressure, and movement.
2. Is Earth's atmosphere heated from above or below? Explain.

Web Video
Coriolis Effect on a Merry-Go-Round

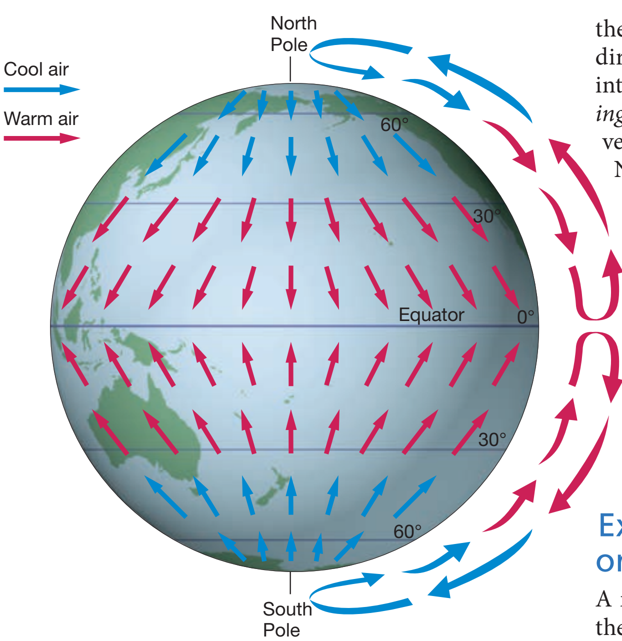

Figure 9 Atmospheric circulation on a nonspinning Earth. A fictional nonspinning Earth with the Sun rotating around Earth directly above Earth's equator at all times. Arrows show the pattern of winds that would develop due to uneven solar heating on Earth.

3 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 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.

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

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

rotates around its center. It has bars that people hang onto while the merry-go-round spins, as shown in **Figure 10**.

Imagine that you are on a merry-go-round that is spinning counterclockwise, as viewed from above (Figure 10). 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 10, *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 10, *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 that you are back 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 (*dashed gray line*). 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 10). A person viewing the merry-go-round from directly overhead would observe that the ball did indeed travel along a straight-line path (Figure 10, *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.

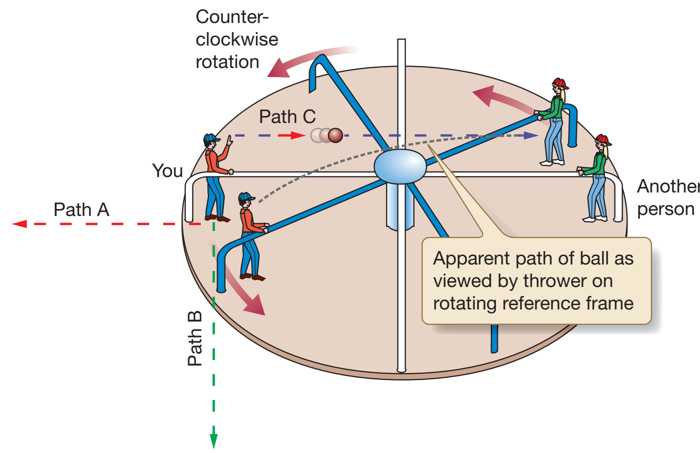

Figure 10 A merry-go-round spinning counterclockwise as viewed from above. See text for description of *Paths A*, *B*, and *C*. The curving dashed gray line shows the apparent path of the ball between the two people as viewed by the thrower on the moving merry-go-round.

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.

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 11a** 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 11b**).

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!