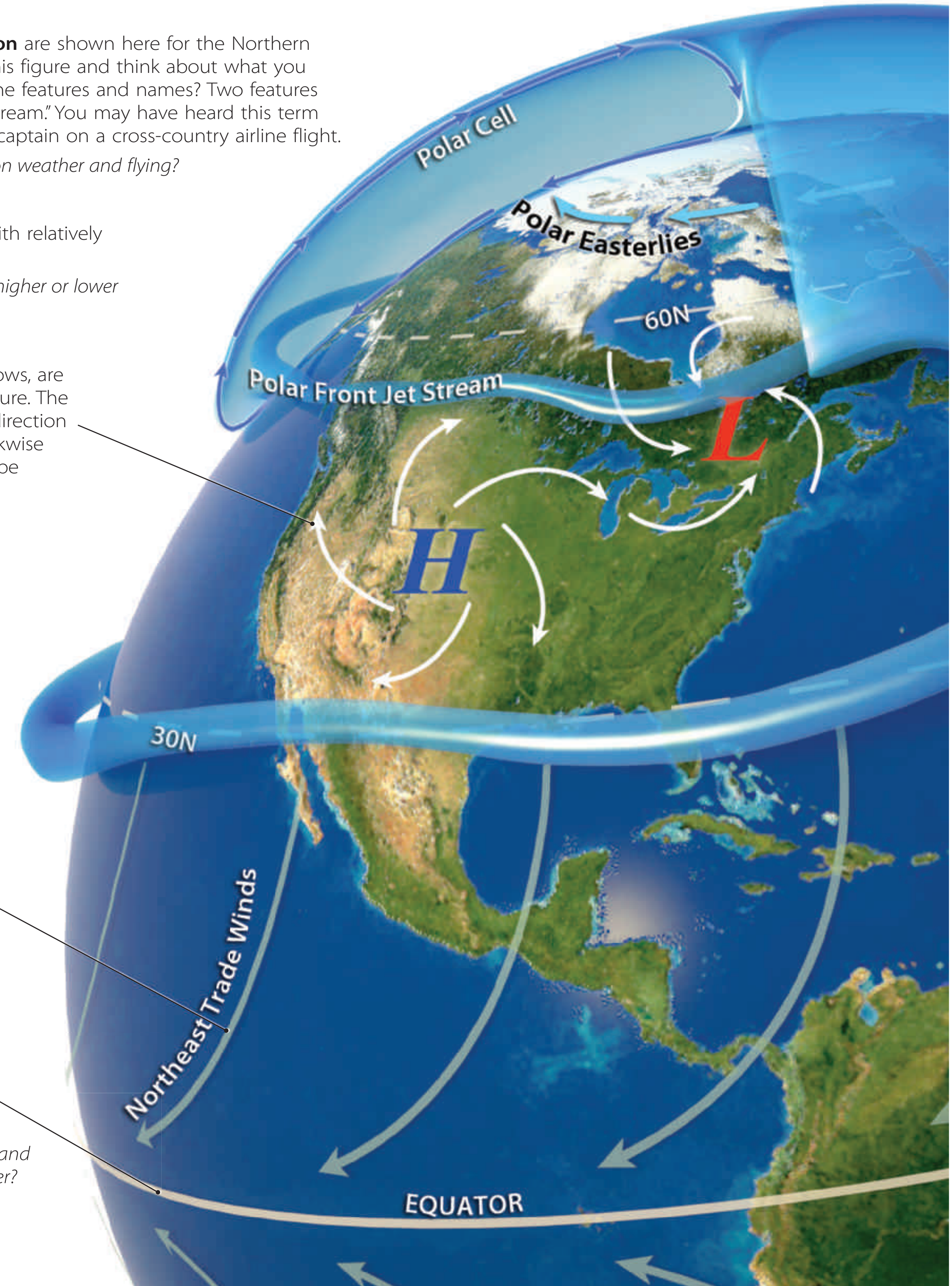
CHAPTER 3

Atmospheric Motion

MOTION OF THE EARTH'S ATMOSPHERE has one of the greatest influences on human lives, controlling climate, rainfall, weather patterns, and long-range transportation. It is driven largely by differences in insolation, with influences from other factors, including topography, land-sea interfaces, and especially rotation of the planet. These factors control motion at local scales, like between a mountain and valley, at larger scales encompassing major storm systems, and at global scales, determining the prevailing wind directions for the entire planet. All of these circulations are governed by similar physical principles, which explain wind, weather patterns, and climate.



Large-scale patterns of atmospheric circulation are shown here for the Northern Hemisphere. Examine all the components on this figure and think about what you know about each. Do you recognize some of the features and names? Two features on this figure are identified with the term "jet stream." You may have heard this term watching the nightly weather report or from a captain on a cross-country airline flight.

What is a jet stream and what effect does it have on weather and flying?

Prominent labels of H and L represent areas with relatively higher and lower air pressure, respectively.

What is air pressure and why do some areas have higher or lower pressure than other areas?

Distinctive wind patterns, shown by white arrows, are associated with the areas of high and low pressure. The winds are flowing outward and in a clockwise direction from the high, but inward and in a counterclockwise direction from the low. These directions would be reversed for highs and lows in the Southern Hemisphere.

Why do wind patterns develop around areas of high and low pressures, why do these patterns spiral, and why are some spirals clockwise and others counterclockwise?

North of the equator, prevailing winds (shown with large gray arrows) have gently curved shapes. For most of human history, transportation routes depended on local and regional atmospheric circulation. These winds were named "trade winds" because of their importance in dictating the patterns of world commerce. The trade winds circulate from Spain southwestward, causing Christopher Columbus to land in the Bahamas rather than the present U.S.

What causes winds blowing toward the equator to be deflected to the west?

Prevailing winds from the north and south converge near the equator. This zone of convergence, called the *Intertropical Convergence Zone (ITCZ)*, is a locus of humid air and stormy weather.

What causes winds to converge near the equator, and why does this convergence cause unsettled weather?

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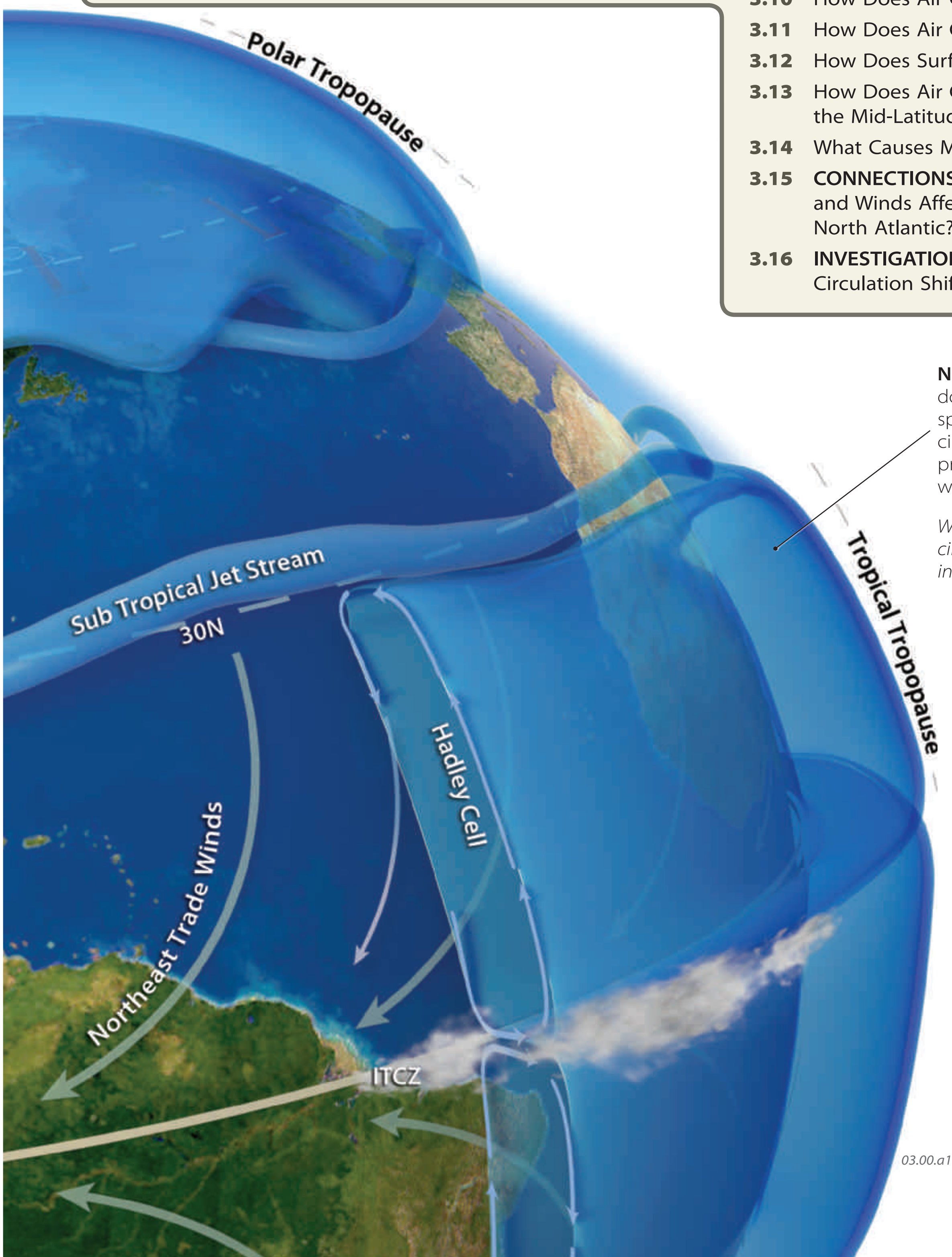


Near-surface winds interact with upward- and downward-flowing air higher in the atmosphere, together forming huge tube-shaped air circuits called *circulation cells*. The most prominent of these are *Hadley Cells*, one of which occurs on either side of the equator.

What controls the existence and location of circulation cells, and how do the Hadley Cells influence global weather and climate?

Motion in the atmosphere affects us in many ways. It controls short-term weather and long-term climate, including typical average, maximum, and minimum temperatures. The large-scale patterns of air circulation, along with effects of local winds, cause some areas to be deserts and others to be rain forests, and cause winds to change direction with the seasons and from night to day. Regional air circulation affects the amount and timing of rainfall for a region, which in turn controls the types of soils, vegetation, agriculture, and animals situated in an area. Winds determine which areas of the U.S. are more conducive to wind-power generation than others. The result of these global, regional, and local atmospheric motions is a world in which the tropics are not too hot, the polar areas are not too cold, and no areas have too little moisture for life.

3.1 How Do Gases Respond to Changes in Temperature and Pressure?

THE ATMOSPHERE CONSISTS LARGELY OF GASES, with lesser amounts of liquids, such as drops of water, and solids, such as dust and ice. By nature, gases expand easily or contract in volume in response to changes in temperature and pressure. Variations in temperature and resulting changes in pressure are the main drivers of motion in the atmosphere.

A How Does a Gas Behave When Heated or Cooled?

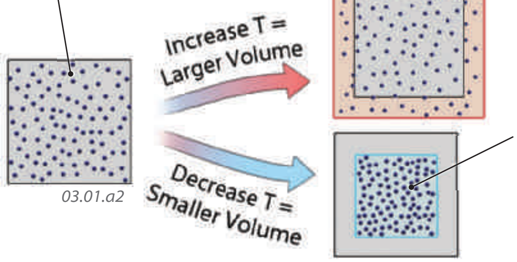
The quantity of insolation entering the atmosphere exhibits considerable spatial variability, especially as a function of latitude, and temporal variations on both daily and seasonal time scales. These variations in insolation in turn lead to differences in temperatures. How do the gases in the atmosphere respond to changes in temperature?

03.01.a1 Namibia, Africa

1. Consider what happens when we want to make a hot-air balloon rise (◀). Typically, a propane-powered burner heats ambient air, causing the air to expand in volume. This increase in volume inflates the balloon. Since the same amount of gas now occupies a much larger volume, the *density* of the heated air is less than the density of the surrounding air, so the balloon rises. So, as air increases in temperature, it tends to increase in volume and become less dense.

2. The figure below shows how a quantity of gas responds to either an increase in temperature (heating) or a decrease in temperature (cooling). The starting condition is represented by the cube of gas on the left.

3. An increase in the temperature of a gas means more energetic molecules, so a larger volume is needed to accommodate the same amount of gas.



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4. If a gas cools, the molecules within it have less kinetic energy (motions) and can therefore be packed into a smaller volume. The gas has a higher density and will tend to sink.

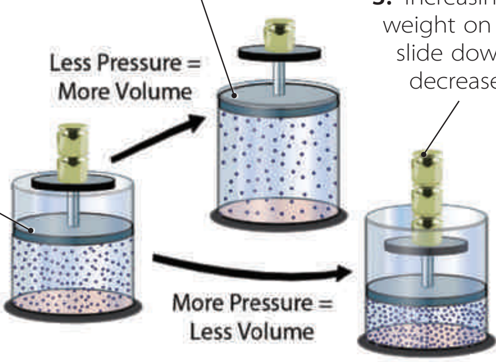
5. This example shows that temperature and volume of a gas are directly related—in fact they are *proportional* if pressure is held constant. Such a proportional relationship means that if temperature is doubled, volume doubles too. If temperature decreases by half, volume does too. This specific relationship is called *Charles's Law*, which is one of the fundamental laws governing the behavior of gases, and it explains why a hot air balloon rises.

B What Happens When a Gas Is Compressed?

If a gas is held at a constant temperature but forced to occupy a smaller *volume*, the *pressure* of the gas increases. Pressure is proportional to the number of collisions of the molecules. If the same gas fills a larger volume, the pressure decreases. In both cases, if we instead change the pressure, the volume of the gas will adjust accordingly. A material, like a gas, that can be compressed, is said to be *compressible*.

1. Molecules of gas in the sealed container in the left canister are under pressure, represented by the two weights resting on top. At some temperature, the molecules have a fixed amount of energy, and some of the moving molecules are hitting the moveable lid, resisting the downward force of the attached weight.

2. Removing a weight reduces the downward pressure on the gas. However, the gas retains its same average energy level (temperature) and therefore exerts the same upward force on the moveable lid as before. The upward force from the gas molecules exceeds the downward force of the weight and so raises the lid, increasing the volume occupied by the gas. In this way, a decrease in pressure results in an increase in volume, if the gas does not change temperature.



03.01.b1

3. Increasing the downward pressure by adding weight on the original canister causes the lid to slide down. This increase in pressure causes a decrease in volume. As the gas is compressed into a smaller volume, the number of the molecules impacting the lid increases. When this upward force from the gas molecules equals the downward force from the weight, the lid stops moving, and the volume and pressure of the gas stop changing.

4. The relationship between pressure and volume of a gas, under conditions of constant temperature, is *inversely proportional*—if pressure increases, volume decreases. If pressure decreases, volume increases. Either pressure or volume can change, and the other factor responds accordingly, changing in the opposite direction by a proportional amount. That is, if the volume is cut in half, the pressure doubles. If the volume doubles, the pressure is cut in half. This inversely proportional relationship between pressure and volume, under constant temperature, is called *Boyle's Law*.

C How Are Temperatures and Pressures Related?

Since Charles's Law relates volume to temperature, and Boyle's Law relates volume to pressure, we might suspect that we can relate temperature and pressure. Combining Charles's Law and Boyle's Law leads to the *Ideal Gas Law*, which relates temperature, pressure, and density (mass divided by volume). Basic aspects of the Ideal Gas Law help explain the processes that drive the motion of matter and associated energy in the atmosphere.

1. We can represent the Ideal Gas Law with a figure, with words, or with an equation. We begin with this figure (▶), which expresses the two sides of the equation. On one side of the equation (the left in this figure) is pressure. On the right side of the equation are density and temperature. What the Ideal Gas Law states is that if we increase a variable on one side of the equation (like increasing pressure), then one or both of the variables on the other side of the equation have to change in the same direction—density or temperature have to also change, or perhaps both do.

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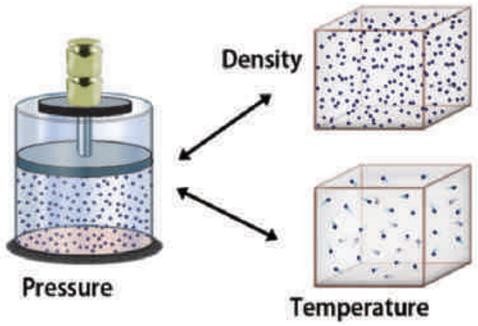

2. Examine this figure and envision changing any one of the three variables (pressure, density, and temperature), and consider how the other two variables would respond to satisfy the visual equation.

3. What happens if pressure increases? If temperature does not change, then density must increase. If pressure increases but density does not change, then temperature has to increase. Alternatively, temperature and density can both change. This three-way relationship partly explains why temperatures are generally warmer and the air is more dense at low elevations, where the air is compressed by the entire weight of the atmosphere, than at higher elevations, where there is less air. Higher pressure often results in higher temperatures.

4. What does the relationship predict will happen if a gas is heated to a higher temperature? If the density does not change, the pressure exerted by the gas on the plunger must increase. If the pressure does not change, the density must decrease. This is because density and temperature are on the same side of the equation, so an increase in one must be matched by a decrease in the other—if the other side of the equation (pressure) does not change. The relationship indicates that heated air can become less dense, which allows it to rise, like in a hot air balloon.

5. The Ideal Gas Law can also be expressed by the equation to the right:

$$P = R \rho T$$

where P is pressure, R is a constant, ρ is density (shown by the greek letter rho), and T is temperature. Note how this equation roughly corresponds to the figure above.

D How Can Differences in Insolation Change Temperatures, Pressures, and Density in the Atmosphere?

The way gas responds to changes in temperature and pressure is the fundamental driver of motion in the atmosphere. Since temperature changes are largely due to insolation, we can examine how insolation affects the physical properties of gas and how this drives atmospheric motion.

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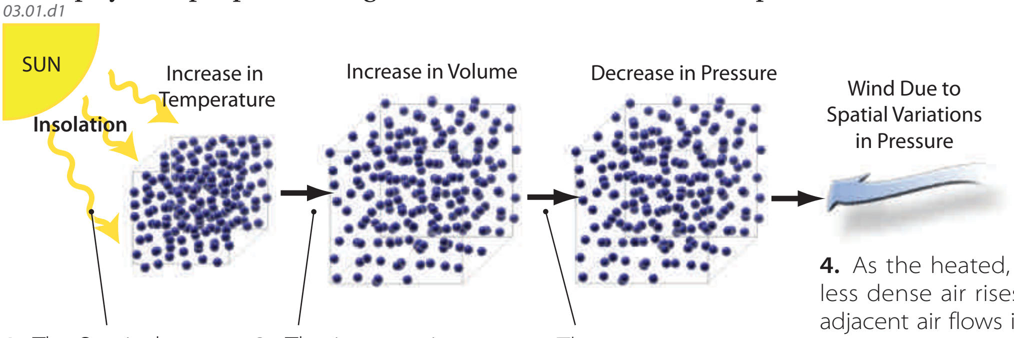


1. The Sun is the major energy source for Earth's weather, climate, and movements of energy and matter in the atmosphere and oceans. In the figure above, insolation strikes Earth's surface (land or water), which in turn heats a volume of gas in the over-lying atmosphere.

2. The increase in temperature results in expansion of the gas because of the increased kinetic energy of the molecules in the gas, which is an increase in volume. If the same number of gas molecules occupy more volume, the density of the air decreases (the air becomes less dense).

3. The increase in volume can result in a decrease in pressure (less frequent molecular collisions). As a result, the air mass is now less dense than adjacent air that was heated less. The more strongly heated and expanded air rises because it is less dense relative to surrounding air (which was not heated as much and so is more dense).

4. As the heated, less dense air rises, adjacent air flows into the area to replace the rising air. The end result is a vertical and lateral movement of air within the atmosphere—vertical motion within and above the rising air, and lateral motion of surrounding air toward the area vacated by the rising air.

5. In this way, the response of gas to changes in temperature, pressure, and density (or volume), as expressed by the gas laws, is the primary cause of motion in the atmosphere. Variations in insolation cause changes in temperature, pressure, and density, which in turn cause air to move within the atmosphere.

Before You Leave This Page Be Able To

- ✓ Explain why a gas under constant pressure expands and contracts with changes in temperature.
- ✓ Explain why a gas at a constant temperature expands or contracts with changes in pressure.
- ✓ Sketch and summarize the Ideal Gas Law and how the three gas laws explain motion in the atmosphere due to variations in insolation.

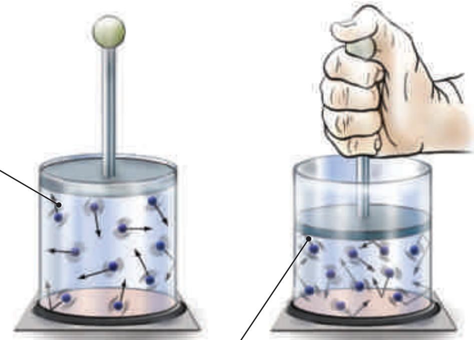
3.2 What Is Air Pressure?

PRESSURE OF GASES WITHIN THE ATMOSPHERE is highly variable, both vertically and laterally. These variations in pressure define the structure of the atmosphere and also determine the nature and direction of atmospheric motions. If one place in the atmosphere has higher pressure than another place, this imbalance of pressure (and therefore also atmospheric mass) must be evened out, causing the air to flow. How do we describe and measure pressure, and how do we use these measurements to understand or even predict the flow of air?

A What Is Pressure?

Pressure is an expression of the force exerted on an area, usually from all directions. In the case of a gas, pressure is related to the frequency of molecular collisions, as freely moving gas molecules collide with other objects, such as the walls of a container holding the gas. It is such collisions that keep a balloon, soccer ball, or bicycle tire inflated.

1. Molecules of gas in a sealed glass container move rapidly in random directions, and some strike the walls of the container. The force imparted by these collisions is pressure. The more collisions there are, the more pressure is exerted on the walls of the container.



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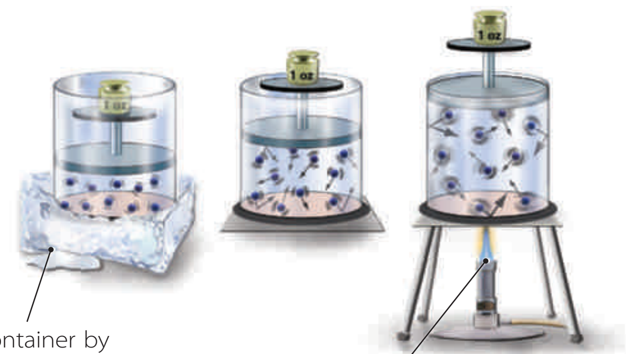
2. If we push down on the lid of the container, the same number of molecules are confined into a smaller space. Lower parts of the container walls are now struck by a greater number of the more closely packed gas molecules, so the pressure is greater. Decreasing the volume of a gas increases its pressure, consistent with Boyle's Law.

3. What happens if we put a weight (▶) on top of the lid (center container) and then either cool or heat the gas in the container?



03.02.a2

4. If we cool the container by placing it in ice, the molecules become less energetic and so strike the walls and lid of the container less often—the gas pressure decreases and the lid moves down.

5. If we instead heat the container, the gas molecules become more energetic and strike the walls and lid of the container more often—the gas pressure increases and lifts the lid.

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6. The equation to the right illustrates what pressure measures and the units we use to describe it. The units of pressure are used throughout this book in describing weather, climate, and the flow of water.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{\text{Mass} \cdot \text{Acceleration}}{\text{Area}} = \frac{\text{kg m sec}^{-2}}{\text{m}^2} = \frac{\text{Newtons}}{\text{m}^2} = \text{Pascals}$$

100 Pascals = 1 millibar (mb)

7. Pressure is a force exerted on a given surface area.

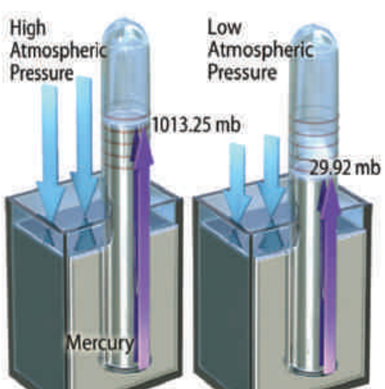
8. According to Newton's second law, force is the product of mass and acceleration.

9. The unit of mass is the kilogram (kg), acceleration is in meters/second/second (m/s^2), and area is in square meters (m^2).

10. A force of one kg m/s^2 is called a *Newton*. Pressure, measured in Pascals, is an expression of the number of Newtons of force exerted on a square meter of surface.

11. The air pressure at Earth's surface is many Pascals, so we express pressures in a larger, related unit called a *bar*, or in *millibars* (1/1000 of a bar).

B How Is Air Pressure Measured?



03.02.b1

◀ We can measure air pressure with an instrument called a *barometer*. The barometer shown to the left is a sealed glass tube fixed in liquid mercury. Changes in air pressure cause the liquid level in the tube to rise or fall, allowing the measurement of relative pressure. Such barometers have units of *inches (or centimeters) of mercury*. Pressure is also reported in units of a *bar*, with one bar being approximately equal to the average air pressure at sea level. Modern digital instruments record pressure in millibars.

▶ Meteorologists measure air pressure at vertical heights in the atmosphere using hydrogen- or helium-filled balloons, like this one. An instrument package called a *radiosonde* is suspended from the balloon (lower left of the photograph). Sensors measure pressure, temperature, humidity, and position (using a GPS) as the balloon ascends, and these measurements are transmitted via radio to a central computer. Wind speed and direction are inferred from successive positions of the radiosonde. The balloon eventually pops and the radiosonde parachutes to the ground.

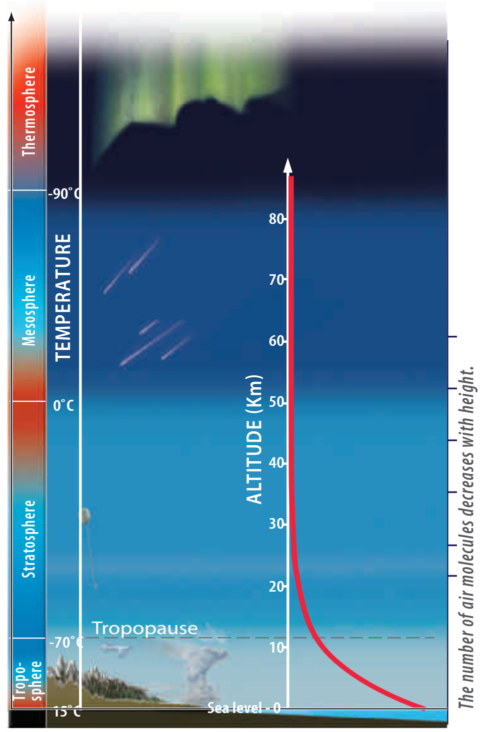
03.02.b2

C How Does Air Pressure Vary Vertically?

1. Air pressure in the atmosphere is not constant. The largest variation is vertically, with an abrupt decrease in pressure upward from near the surface. The red curve on this figure shows how the air pressure, measured in millibars (mb), decreases from Earth's surface to the top of the atmosphere.

2. This diagram depicts the main layers of the atmosphere (troposphere, stratosphere, etc.) and highlights some of the features observed in each part, such as auroras in the thermosphere, shooting stars that mostly burn up in the mesosphere, and the restriction of most clouds and weather to the troposphere.

3. Colors along the left edge of the diagram convey temperature variations within and between the atmospheric layers. These vertical temperature variations affect the density of the air, impacting air motions caused by the Sun heating the Earth's surface.



03.02.c1

4. In the thermosphere and mesosphere, gas molecules are relatively sparse and temperatures are low (–90°C at the thermosphere-mesosphere boundary). As a result of the sparseness of molecules, air pressures are very low (less than one millibar).

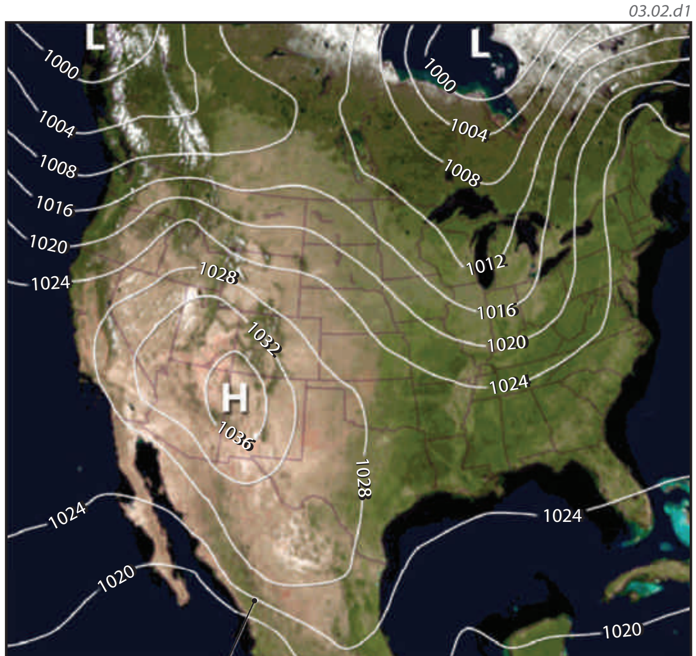
5. The abundance of gas molecules increases down into the stratosphere, and this is accompanied by an increase in air pressure (the bending of the red curve to the right as it goes downward). Air pressures are slightly greater at the top of the stratosphere than in the overlying mesosphere, but at the base of the stratosphere (the tropopause) they have increased to about one-fifth of pressures measured at sea level.

6. The pull of Earth's gravity holds most gas molecules close to Earth's surface, in the troposphere. Air pressure increases downward in the troposphere because of a greater abundance of molecules downward and the larger total number of molecules pressing down from the layers above. The highest air pressures are close to the surface, and at the lowest elevations. Sea level is the reference level for air pressure, with an average pressure of 1,013 mb (a little over 1 bar).

D How Does Air Pressure Vary Laterally?

1. Air pressure also varies laterally, from area to area, and from hour to hour, and these variations are typically represented on maps, like the one shown here. Such maps either show the pressure conditions at a specific date and time or show pressure values averaged over some time period, like a month or a year. To allow us to compare different regions and to see the larger patterns, the map uses pressure values that are corrected to sea level, or their sea-level equivalent. In this way, we eliminate the effects of differences in elevation from place to place.

03.02.d1



2. Such maps of air pressure contain numbered lines, called *isobars*, that connect locations with equal pressure. If you could follow an isobar across the countryside, you would follow a path along which the pressure values, once corrected to their sea-level equivalents, would be equal. Successive isobars are numbered to represent different values of air pressure, usually in millibars (e.g., 1,020), and there is generally a constant difference in pressure between two adjacent isobars (a 4 mb difference on this map). Note that isobars do not cross, but can completely encircle an area.

3. Most maps of air pressure feature the large capital letters H and L. An H represents an area of relatively higher pressure called a high-pressure area or simply a *high*. An L represents a low-pressure area, commonly called a *low*. An elongated area of high pressure can be called a *ridge* of high pressure and an elongated area of low pressure is a *trough*.

4. The map patterns change with time, corresponding to changes in air pressure that accompany changes in weather. Patterns typical for a region also change from season to season.

Before You Leave This Page Be Able To

- ✓ Describe the concept of pressure, what it represents, and how it changes when subjected to changes in temperature and volume.
- ✓ Explain how we measure pressure and what units we use.
- ✓ Sketch and explain how air pressure varies vertically in the atmosphere.
- ✓ Describe what a map of pressure shows, and explain the significance of an isobar, H, and L on such a map.

3.3 What Causes Pressure Variations and Winds?

THE MOVEMENT OF AIR IN THE ATMOSPHERE produces *wind*, or movement of air relative to Earth's surface. Circulation in the atmosphere is caused by pressure differences generated primarily by uneven insolation. Air flows from areas of higher pressure, where air sinks, to areas of lower pressure, where air rises.

A How Do We Measure the Strength and Direction of Wind?

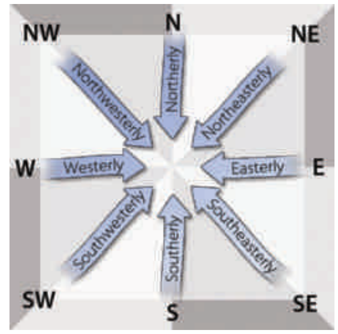
Wind speed and direction are among the most important measurements in the study of weather and climate. On short time scales, wind can indicate which way a weather system is moving and the strength of a storm. When considered over longer time scales, winds indicate general atmospheric circulation patterns, a key aspect of climate.

03.03.a1

1. Wind directions can be assessed as easily as throwing something light into the air and tracking which way it goes, but it is best done with a specially designed measuring device (◀) that can measure the wind speed and direction. Wind speed is expressed in units of distance per time (km/hr) or as knots, which is a unit expressing nautical miles per hour. One knot is equal to 1.15 miles/hr or 1.85 km/hr.

2. Wind direction is conveyed as the direction *from which the wind is blowing*. Wind direction is commonly expressed with words (▶), such as a northerly wind (blowing from the north). It can instead be described as an *azimuth* in degrees clockwise from north. In this scheme, north is 0°, east is 090°, south is 180°, and west is 270°.

03.03.a2

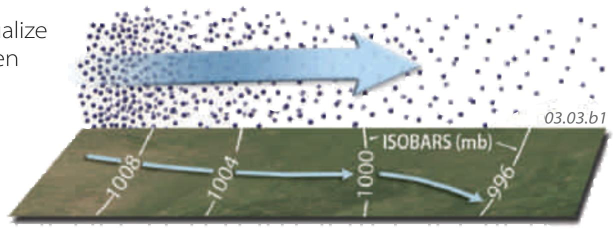


3. The atmosphere also has vertical motion, such as convection due to heating of the surface by insolation. A local, upward flow is an *updraft* and a downward one is a *downdraft*.

B What Causes Air to Move?

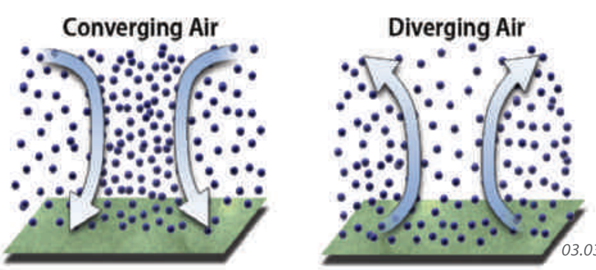
Air moves because there are variations in air pressures, in density of the air, or in both (recall that pressure and density are related via the Ideal Gas Law). Such pressure and density variations are mostly caused by differential heating of the air (due to differences in insolation) or by air currents that converge or diverge. The atmosphere is not a closed container, so changes in volume (i.e., air being compressed or expanded) come into play. These volume changes can make air pile up or spread out, resulting in variations in air pressure.

1. Movement of air occurs to equalize a difference in air pressure between two adjacent areas (▶), that is, a *pressure gradient*. Air molecules in high-pressure zones are packed more closely together than in low-pressure zones, so gas molecules in high-pressure zones tend to spread out toward low-pressure zones. As a result, air moves from higher to lower pressure, in the simplest case (as shown here) perpendicular to isobars.



03.03.b1

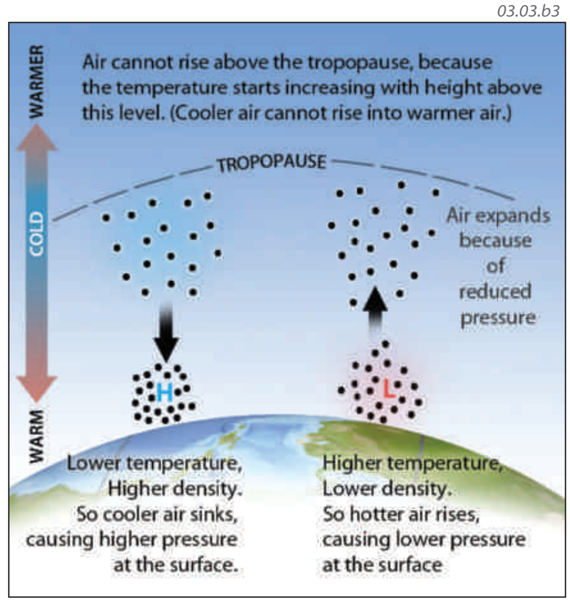
2. High-pressure zones and low-pressure zones can be formed by atmospheric currents that converge or diverge (▼). *Converging* air currents compress more air into a smaller space, increasing the air pressure. *Diverging* air currents move air away from an area, causing low pressure. Forces associated with converging and diverging air are called *dynamic forcing*.



03.03.b2

3. Most variations in air pressure and most winds, however, are caused by thermal effects, specifically differences in insolation from place to place. This cross section (▶) shows a high-pressure zone caused by the sinking of cold, high-altitude air toward the surface. In the adjacent low-pressure zone, warmer near-surface temperatures have caused air to expand, become less dense, and rise, causing low pressure. Near the surface, air would flow away from the high pressure and toward the low pressure. Different air currents would form higher, in the upper troposphere, to accommodate the sinking and rising of the air. In an atmosphere that doesn't have strong updrafts or downdrafts, at any altitude the upward pressure gradient will approximately equal the downward force of gravity.

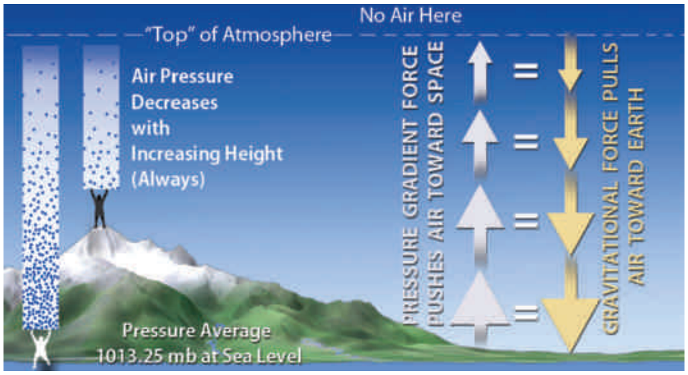
03.03.b3



C What Forces Result from Differences in Air Pressure?

Differences in air pressure, whether caused by thermal effects or dynamic forcing, result in a *pressure gradient* between adjacent areas of high and low pressure. Associated with this pressure gradient are forces that cause air to flow. Pressure gradients can exist vertically in the atmosphere or laterally from one region to another.

03.03.c1

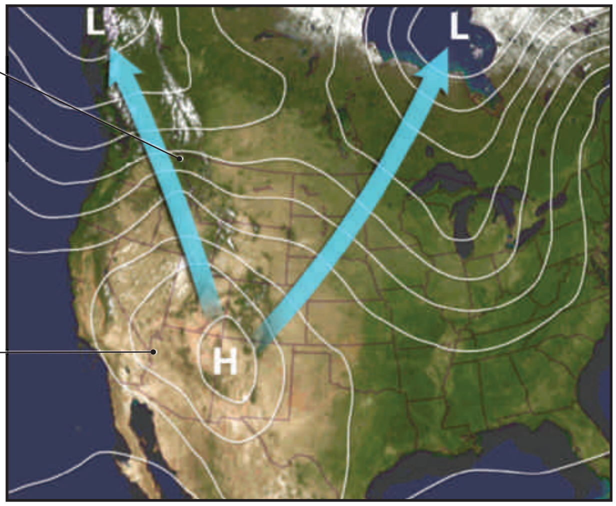


1. Elevation differences cause the largest differences in air pressure. At high elevations, there is less atmospheric mass overhead to exert a downward force on the atmosphere. As a result, density decreases with elevation, and air pressure does too.

2. These vertical variations in air pressure cause a pressure gradient in the atmosphere, with higher pressures at low elevations and lower pressures in the upper atmosphere. This pressure gradient can be thought of as a force directed from high pressures to lower ones. This *pressure-gradient force* is opposed by the downward-directed force of gravity, which is strongest closer to Earth's surface.

3. Lateral variations in air pressure also set up horizontal pressure gradients, and a pressure-gradient force directed from zones of higher pressure to zones of lower pressure. On the map below, the pressure-gradient force acts to cause air to flow from high pressure toward lower pressures, as illustrated by the blue arrows on the map.

03.03.c2



4. Places where isobars are close have a steep pressure gradient, and a strong pressure-gradient force, so movement of the atmosphere (i.e., winds) will generally be strong in these areas.

5. Places where isobars are farther apart have a more gentle pressure gradient, a weak pressure-gradient force, and generally lighter winds. Although winds tend to blow from high to low pressure, other factors, such as Earth's rotation, complicate this otherwise simple picture, causing winds patterns to be more complex and interesting.

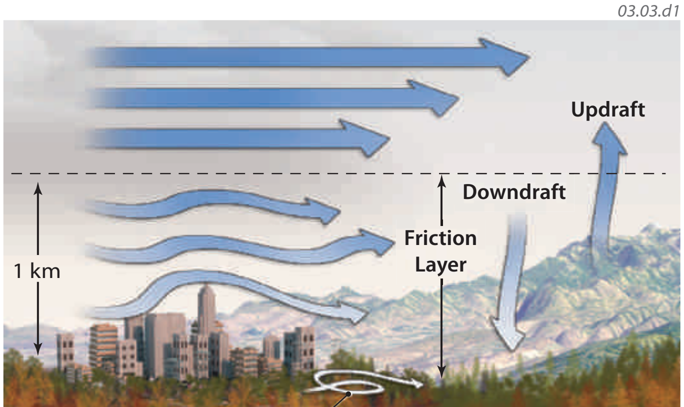
D How Does Friction Disrupt Air Flow?

As is typical for nature, some forces act to cause movement and other forces act to resist movement. For air movements, the pressure-gradient force acts to cause air movement and friction acts to resist movement.

1. Friction occurs when flowing air interacts with Earth's surface.

2. As represented in this figure by the shorter blue arrows low in the atmosphere, wind is slowed near the surface, because of friction along the air-Earth interface. As the air slows, it loses momentum (which is mass times velocity). Some momentum from the moving air can be transferred to the land, such as when strong winds pick up and move dust or cause trees to sway in the wind. It is also transferred to surface waters, causing some currents in oceans and lakes and forming surface waves.

03.03.d1



3. Friction with Earth's surface, whether land or water, also causes the wind patterns near the surface to become more complicated. On land, air is forced to move over hills and mountains, through valleys, around trees and other plants, and over and around buildings and other constructed features. As a result, the flow patterns become more curved and complex, or *turbulent*, near the surface, with local flow paths that may double back against the regional flow, like an eddy in a flowing river. Friction from the surface is mostly restricted to the lower 1 km of the atmosphere, called the *friction layer*.

4. Stronger winds occur aloft, in part because these areas are further removed from the frictional effects of Earth's surface. Some friction occurs internally to the air, even at these heights, because adjacent masses of air can move at different rates or in different directions. Friction can also accompany vertical movements in updrafts and downdrafts.

Before You Leave This Page Be Able To

- ✓ Explain how we measure and describe wind velocity and direction.
- ✓ Sketch and explain how air motion and heating can form zones of low and high pressure.
- ✓ Describe the pressure-gradient force.
- ✓ Sketch and explain how friction affects wind.

3.4 How Do Variations in Temperature and Pressure Cause Local Atmospheric Circulation?

PRESSURE GRADIENTS INDUCE FLOW at all scales, including local and regional ones, arising from unequal heating by insolation and latent heat, by differing thermal responses of land versus sea, and even from the construction of large metropolitan areas. Such circulations contribute to the climate of a place, particularly in the absence of, or interaction with, more powerful circulations.

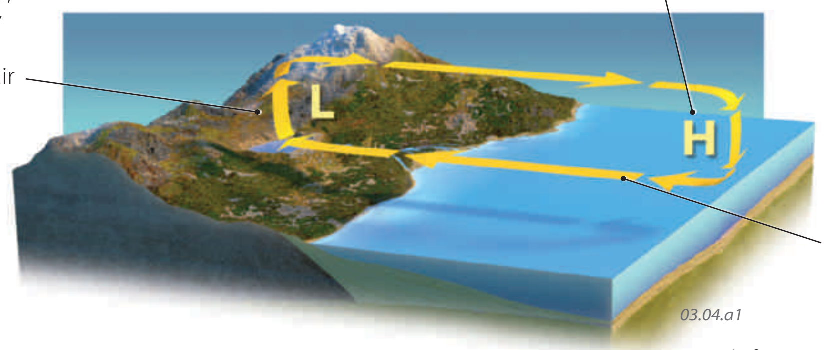
A What Causes Breezes along Coasts to Reverse Direction Between Day and Night?

People who live along coasts know that gentle winds sometimes blow in from the sea and at other times blow toward the sea. The gentle winds are called a *sea breeze* if it blows from sea in toward the land and a *land breeze* if it blows from the land out to sea. Such breezes are mostly due to differences in the way that land and sea warm up during the day and cool down at night.

The Sea Breeze (Daytime)

1. During daytime hours, land heats up significantly, particularly in summer. Land, which has a lower specific heat capacity than water, heats up more overall and more rapidly than water does. The hot air over the land surface rises, inducing a local low-pressure area over the land.

2. At the same time, air over the water body is cooled by the relatively cool water temperatures and by cooling associated with evaporation. The relatively cool air over the water sinks, inducing a local high-pressure area over the water.

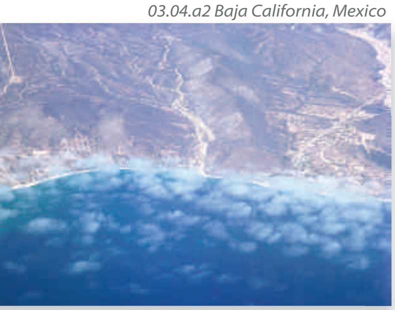


03.04.a1

3. The difference between the low pressure over land and the high pressure over the water represents a pressure gradient. The associated pressure-gradient force pushes air near the surface, from higher pressure to lower pressure. This flow is an *onshore breeze* or *sea breeze* that feels cool to people on the beach.

4. Air aloft moves in the opposite direction, from land to sea. This is a response to an upper-level pressure gradient caused by the "extra" air rising over land and less upper-level air over the sea, due to air sinking.

03.04.a2 Baja California, Mexico



5. In this photograph (◀), heating of the hot, desert land causes air over the land to rise, drawing in moist air from the adjacent water. Rising of the moist air along the coast forms thin, scattered clouds, but can draw in much thicker masses of clouds, forming coastal fog and overcast skies.

The Land Breeze (Nighttime)

1. At night, land cools significantly, particularly if there isn't much cloud cover. The relatively cool air over the land surface sinks, inducing a surface high-pressure area. Sometime in the evening hours, the surface low over the land weakens and becomes a high.

2. The water body doesn't cool as much at night, partly because of water's higher specific heat capacity and because of mixing. So air over the water stays relatively warm compared to the air over the land. Therefore, this air rises, generating relatively low pressure over the water body.

03.04.a3

3. The difference between the high pressure over land and the low pressure over the water is a pressure gradient. The pressure-gradient force pushes near-surface air from higher to lower pressure, from the land to the water as an *offshore breeze* or *land breeze*.

4. Aloft, the pressure-gradient force causes the air that rose over the low to return to land to replace the air that sank to create the surface high.

5. The strength of sea and land breezes is proportional to the temperature gradient. The land breeze circulation strengthens through the night, begins to weaken at sunrise, stops sometime in the morning, and then reverses to a sea breeze, when it strengthens until peaking in the afternoon.

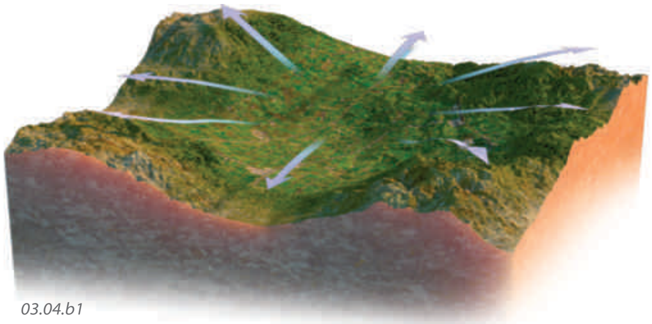
03.04.a4 Philippines

6. In this photograph (◀), an early morning offshore flow, from the land to the sea, pushes moist air offshore, moving clouds out to sea and causing clear conditions along the shoreline.

B How Does Topography Cause Pressure Gradients?

On land, topography can cause pressure gradients and winds that blow in different directions during the day versus at night. These are primarily related to differences in the way land and the atmosphere heat up and cool down, and to temperature differences as a function of elevation.

1. The Sun heats the surface more efficiently than it heats the atmosphere. During the day, the land heats up and in turn heats the adjacent air. Such heated air from lower elevations is especially warm and rises (▶), causing upslope winds, known as a *valley breeze*, or *anabatic wind*. Air that is farther from the surface, aloft in the center of the figure shown here, is less heated and so sinks to replace the rising air. Upslope winds are most obvious when winds from other types of circulation, like storms, are weak.



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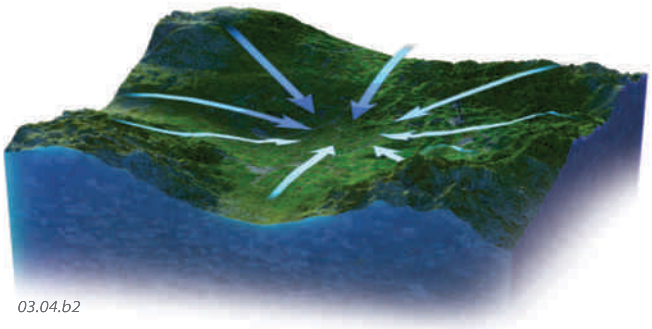


03.04.b2

2. At night, the situation is reversed (◀). With no insolation to warm the surface, the surface will cool more rapidly than the air above it, as it emits longwave radiation to the atmosphere. Thus, the land and adjacent air at higher elevations cools significantly, and the resulting relatively cool surface air will move downslope, producing a *mountain breeze*, or *katabatic wind*. The cool air displaces warmer air in the valley upward, where it can flow to replenish the air lost at higher elevations. The end result is that valley bottoms can be substantially colder at night than areas at a slightly higher elevation.

3. Pollution in rugged terrain is mostly produced in the valleys where people are more likely to live, so the daytime valley breezes push polluted air upslope. But if the pollution is too intense or the slopes are too high and steep to push the air over the ridges and peaks before nightfall, the mountain breeze will send the polluted air back down into the valley to join the new polluted air produced during the next day. The cycle repeats day after day. Persistent high pressure (with its sinking air) over the area can make the situation even worse. Some of the poorest air quality exists in valleys surrounded by higher terrain, such as Mexico City.

C How Do Urban Areas Affect Pressure Features?

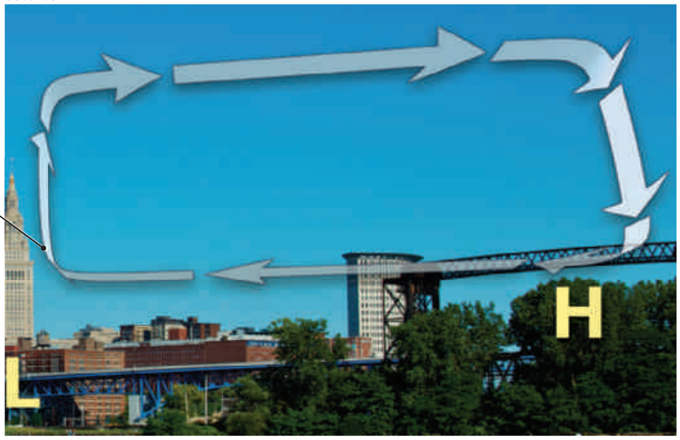
Human development of land can cause pressure gradients as natural ground cover is replaced by buildings, asphalt, and concrete. These human-produced materials have different properties from those of natural materials, and the resulting temperature differences can cause pressure differences.

1. Urban areas, such as cities and towns, are usually warmer than the surrounding rural environments, for several reasons. Urban areas often lack trees for shade and standing water for latent heating rather than sensible heating. They contain waste heat from engines, street lights, and fireplaces, along with urban building and road materials that absorb intense heat. The urban area causes the air to heat up more than air in the less developed surroundings. The warmer air over the city is less dense and rises, leaving behind a local low-pressure area.

2. The outlying areas are generally cooler because they are more likely to contain vegetation for shading and near-surface water, which absorbs insolation for latent heat rather than sensible heating. Outlying areas also have less human-generated waste heat.

3. This phenomenon is known as the *urban heat island* (UHI). Urban-rural temperature differences usually peak in the evening hours, after a day of surface heating and busy human activities that generate the urban heating. The UHI is responsible for some of the modern observed increase in surface temperatures.

03.04.c1



4. This urban-caused circulation of air can redistribute heat and pollution from the city center to outlying suburban and rural areas. Polluted air can be lifted out of the urban area, flow laterally, and descend into outlying areas. Higher pressure in the outlying areas may trap pollution near the ground. As with the sea breezes and valley breezes, the urban heat island can be diminished by storms and other strong air-circulation patterns.

Before You Leave This Page Be Able To

- ✓ Sketch, label, and explain the formation of sea and land breezes.
- ✓ Sketch, label, and explain the formation of valley and mountain breezes.
- ✓ Sketch, label, and explain what an urban heat island is and how it can cause the flow of air and pollution.

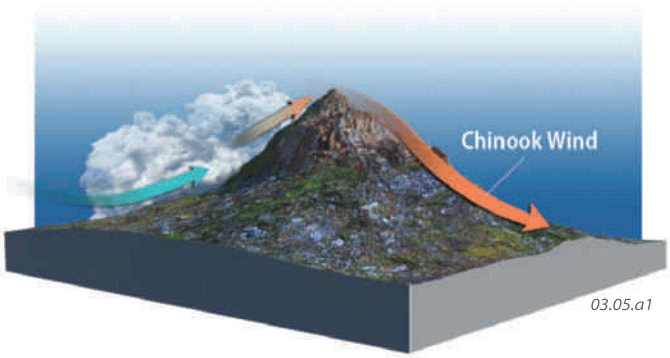
3.5 What Are Some Significant Regional Winds?

DIFFERENCES IN AIR PRESSURE cause a variety of regional to local wind conditions, such as those associated with storms, which are discussed in the chapter on weather. Some local winds are not so much related to weather systems as they are to differences in pressure that tend to occur at certain times of the year or after the establishment of an area of high pressure. These local to regional winds have interesting names, like Chinook winds or Santa Ana winds, and can have profound impacts on people.

A What Is a Chinook Wind and Where Do They Form?

The term *Chinook* originated in the Pacific Northwest and can refer to several types of winds. The most common usage is for a warm, dry wind that blows down the flanks of a mountain range. Chinooks are so warm and dry they are called "snow eaters," for the way in which they can cause a sudden melting of snow and ice on the ground. The onset of a Chinook wind can cause a sudden rise in temperatures, especially during the winter. A Chinook in Loma, Montana, caused temperatures to rise from −48°C (−59°F) to 9°C (49°F) within a 24-hour period, the most change recorded for a single day in the U.S. In Spearfish, South Dakota, a Chinook off the adjacent Black Hills caused temperatures to rise 27 C° (49 F°) in two minutes, the world's fastest rise in temperature ever recorded!

1. This figure depicts the formation of a *Chinook wind*. The process begins when winds push moist air against the *windward* side of a mountain, where windward refers to the side toward which wind is blowing (the left of the mountain in this figure). As the moist air rises up the mountain, it cools, causing the formation of clouds, a process that also releases latent heat. The heat warms the air, which continues rising toward the mountain peaks.



03.05.a1

2. Once the air reaches the peak, it begins flowing down the other side—the *leeward* side, of the mountain (the side opposite the windward side). As the air descends, it continues drying out and is compressed and heated. It is also warm from the release of latent heat on the windward side. The warm, dry air descends from the mountain and spreads across the adjacent lowland, forming a Chinook wind.

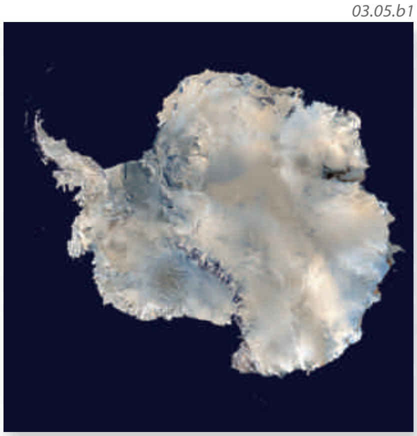
03.05.a2

3. This map shows the locations where Chinook winds are relatively common. As expected, Chinooks occur on the leeward side of mountain ranges (prevailing winds are from the west to east in this region), in Alaska, and elsewhere.

B How Do Katabatic Winds Affect Polar Regions?

1. On the previous two pages, we introduced the term *katabatic wind* for a wind that blows downslope, forming a cool *mountain breeze*. More regional and pronounced katabatic winds affect Antarctica and Greenland, both of which have a high central landmass surrounded by ocean. Air over the middle of the landmasses is very cold and so very dense, flowing off the central topographic highs and down the icy slopes.

03.05.b1



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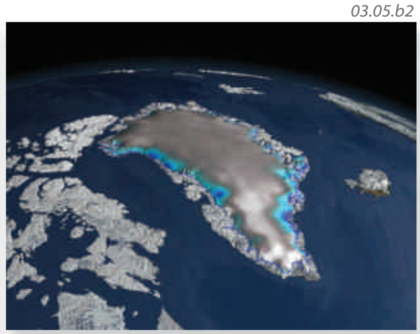


2. These two perspective views show that Antarctica (on the left) and Greenland (on the right) both have a broad, high area centered in the middle of the ice. Katabatic winds blow down off these high areas in all directions. These winds are especially strong where they are channeled down valleys, such as the famous Dry Valleys of Antarctica, so named because strong katabatic winds have stripped most ice off the land surface.

03.05.b3 Antarctica

3. Katabatic winds in Antarctica generally involve cold but dry air, but they can interact with clouds along the coast, sometimes creating stunning effects as the cold air and clouds spill off the highlands, similar to the scene in the photograph above.

C How Do Santa Ana Winds Affect Southern California?

Winds in Southern California typically blow from west to east, bringing relatively cool and moist air from the Pacific Ocean eastward onto land, especially in areas right along the coast, like Los Angeles and San Diego. These coastal cities also often have onshore sea breezes during the day and offshore land breezes at night. At other times, however, regional winds, called *Santa Ana winds*, blow from the northeast and bring dry, hot air toward the coast, causing hot, uncomfortable weather and setting the stage for horrendous wildfires.

Setting of Santa Ana Winds

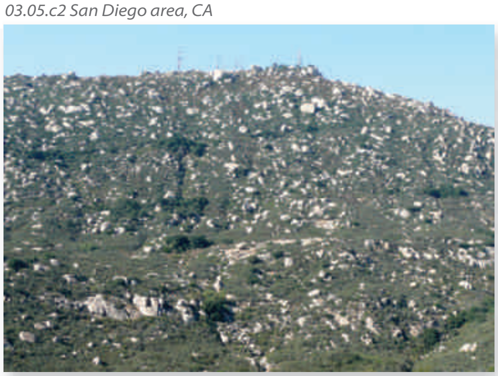
1. *Santa Ana winds* are regional winds that blow from the northeast (▶), typically developing during spring and fall, when high pressure forms over the deserts of eastern California and Nevada. Circulation of air associated with the area of high pressure pushes winds south and westward, toward the coast, in marked contrast to the normal onshore flow. This air is coming from the Mojave Desert and other desert areas to the north and east, so is very dry. The winds bring this dry air southwestward across the very dry Mojave Desert and toward the coast.

03.05.c1

2. Santa Ana winds from the Mojave Desert are partially blocked by the mountains on the northern and eastern sides of Los Angeles. The winds spill through mountain passes, such as Cajon Pass northeast of Los Angeles, and are funneled down the canyons and into the Los Angeles basin. The funneling effect causes winds to be especially strong within the canyons. As the air moves from higher deserts to the northeast and down toward Los Angeles, the air compresses and heats up. As a result, during an episode of Santa Ana winds, the coastal areas of Southern California experience much hotter and drier weather conditions than are normal. Due to this behavior of air flowing from high to low areas, Santa Ana winds are considered to be a type of katabatic wind.

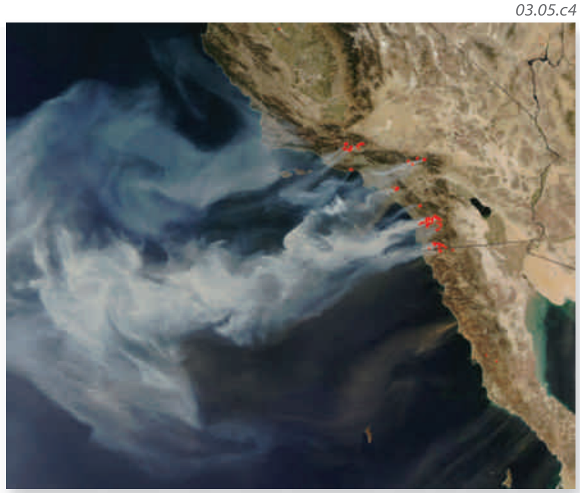
Effect on Wildfires

03.05.c2 San Diego area, CA



1. The hills and mountains of coastal Southern California receive enough precipitation to be covered with thick brush (▲), such as oak, or by forests at higher elevations. During a Santa Ana wind, the fast winds dry out the brush, trees, and other vegetation, making it extremely prone to wildfires.

03.05.c4



3. This amazing image from NASA (◀) combines a satellite image of Southern California and adjacent states with the locations of fires (shown in red), as determined by processing a different kind of satellite data. The smoke produced by a number of fires trails off across the Pacific Ocean, clearly showing Santa Ana winds blowing from the northeast. These fires occurred in October of 2007 and killed 9 people and injured dozens of others, destroyed more than 1,500 homes, and burned more than 2,000 km^2 of forest, brush, and neighborhoods. The region was declared a federal and state emergency, as more than one million people were evacuated, the largest such evacuation in California history. The especially large amount of destruction from these fires was due to the combination of strong Santa Ana winds and a prolonged drought that had dried out the natural vegetation.

03.05.c3

2. The hills and mountains of Southern California experience some of the most spectacular but devastating wildfires of any place on the planet (◀). Santa Ana winds push these fires southwestward, toward the cities and through neighborhoods in the foothills. Wildfires associated with Santa Ana winds can burn thousands of homes, causing hundreds of millions of dollars in damage. Pushed by the strong winds down the canyons, the fast-moving fires can cause the deaths of firefighters and people who did not evacuate in time.

Before You Leave This Page Be Able To

- ✓ Sketch and explain the origins of a Chinook and of a katabatic wind.
- ✓ Sketch and summarize the setting of Santa Ana winds and why they are associated with destructive wildfires.

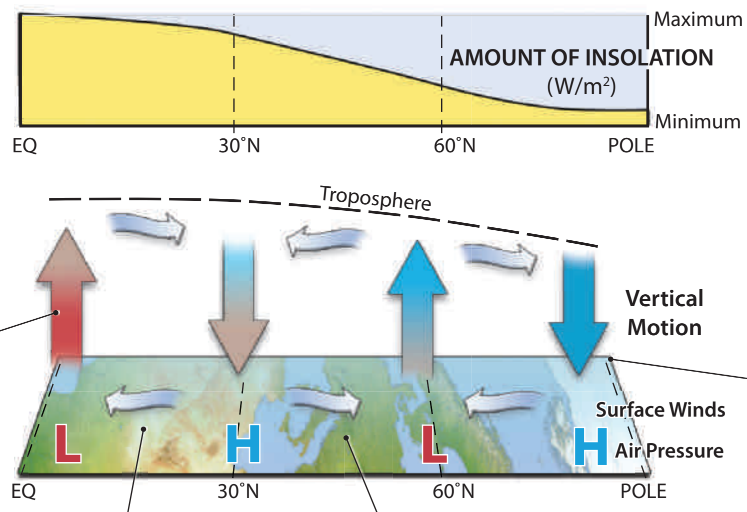
3.6 How Do Variations in Insolation Cause Global Patterns of Air Pressure and Circulation?

SEASONAL AND LATITUDINAL VARIATIONS IN INSOLATION cause regional differences in air pressure, which in turn set up regional and global systems of air circulation. These circulation patterns account for many of the characteristics of a region's climate (hot, cold, wet, dry), prevailing wind directions, and typical weather during different times of the year. Here, we focus on vertical motions in the atmosphere resulting from global variations in insolation and air pressure.

A What Pressure Variations and Air Motions Result from Differences in Insolation?

1. On this figure, the top graph plots the average amount of insolation striking the top of the atmosphere as a function of latitude. On the surface below, the large letters represent high- and low-pressure zones. Arrows show vertical and horizontal airflow and are color coded to convey the overall temperature of air.

2. The maximum amount of insolation striking the Earth is along the equator and the rest of the tropics. This heats up the air, causing the warm air to expand and rise. The expansion and rising results in a zone of surface low pressure in equatorial regions. The upward flow of air helps increase the height of the tropopause over the equator, as shown by the dashed line.



03.06.a1

6. This global pattern of rising and sinking air and resulting low and high air pressures dominates the motion of Earth's atmosphere. The pattern results from variations in insolation and is compensated by horizontal flows, both near the surface and in the upper atmosphere.

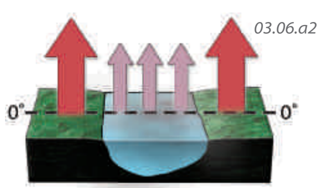
5. The amount of insolation reaches a minimum near the poles. Air near the poles is very cold and dense, sinking to form a zone of high pressure near the surface. The descending air flows away from the pole, toward 60° latitude. In the upper atmosphere, air flows toward the poles to replenish the air that sank.

3. Surface winds flow toward the low pressure to replace the rising tropical air. The rising tropical air cannot continue past the tropopause, so as it reaches these heights it flows away from the equator (EQ) to make room for more air rising from below. This upper-level air descends in the subtropics, near 30° latitude, where it forms a zone of high pressure.

4. The amount of insolation decreases away from the equator, with a relatively sharp drop-off across the mid-latitudes (30° to 60° latitude). Descending air and high pressure in the subtropics causes surface air to flow toward higher latitudes (to the right in this diagram).

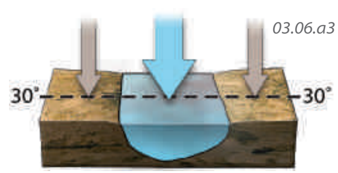
Differences in Responses of Land and Oceans at Different Latitudes

The figures below correspond to the same four regions described above, but focus on differences in behavior between land and water.



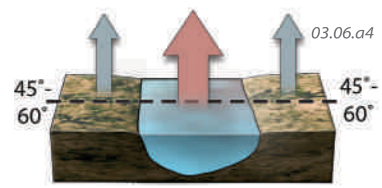
03.06.a2

7. In equatorial regions, which have an energy excess, the rising warm air produces low air pressure. The land warms faster than the sea, so the air is even warmer over the landmasses and the air pressure is correspondingly lower. Rising warm air and low air pressure also prevail over the equatorial oceans, although temperatures tend to be cooler and pressures are not quite so low.



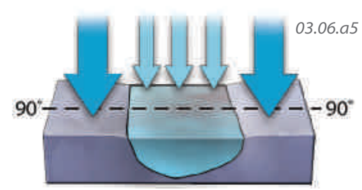
03.06.a3

8. In the subtropics, at approximately 30°, cool air descends from the upper troposphere and causes higher-than-normal air pressures. In the subtropics, oceans are usually cooler than the surrounding continents. Air descending over the oceans will warm up less than air descending over the warmer continents, and so air pressures are particularly high over the oceans.



03.06.a4

9. Air in the mid-latitudes is forced to ascend by surface air converging from the poles and subtropics. This zone has an energy deficit, and oceans retain their energy and are generally warmer than continents. Air forced to rise above the oceans is therefore warmer than that rising over the continents. As a result, the air over the oceans is more likely to rise, and the associated low-pressure zone tends to be stronger over the oceans than over the land.



03.06.a5

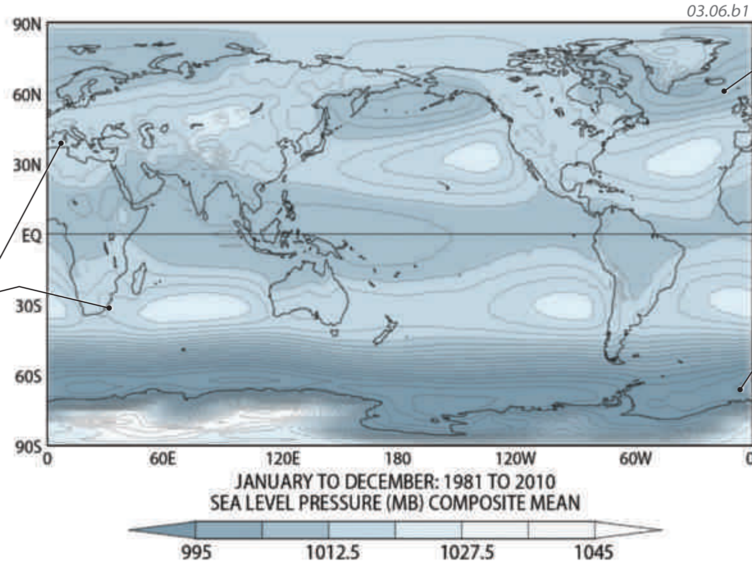
10. The cold, dense, descending air over the poles produces a zone of high air pressure. This zone has a large energy deficit. In such zones, continents lose their energy faster, and are therefore cooler, than the adjacent polar oceans, so air pressures are extremely high over the cold continents. The slightly warmer temperatures of the adjacent oceans diminishes somewhat in these high air pressures.

B How Does Sea-Level Air Pressure Vary Globally?

Average Annual Air Pressure

1. This map shows sea-level equivalent air pressure averaged for 1981 to 2010. Observe the main pattern and compare these patterns with the figures on the previous page. Can you explain the larger patterns on this map?

2. Two belts of high pressure (shown in light gray) encircle the globe at about 30° N and 30° S (the subtropics). Between these two is a belt of lower pressure (shown in medium gray) straddling the equator, in the tropics. The equatorial low pressure and flanking high-pressure zones are due to the large air current that rises in the tropics and descends in the subtropics.



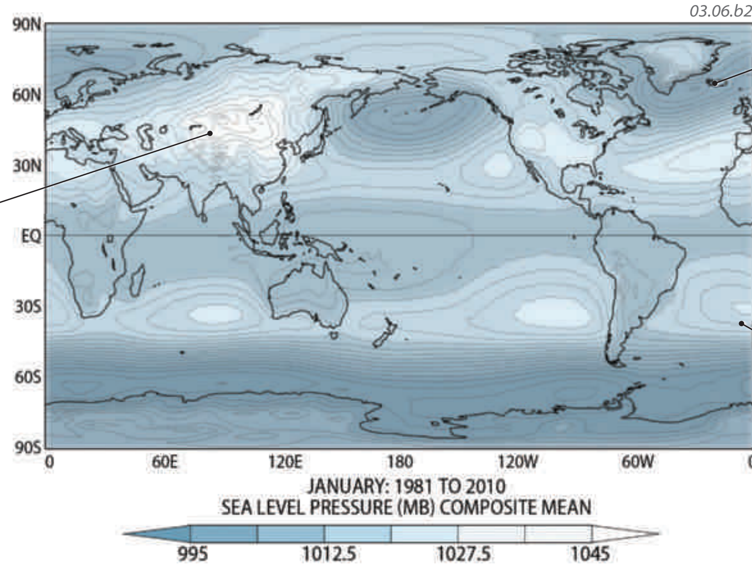
3. A set of low-pressure areas occurs near 60° N. Note that the lows are best developed in the oceans, and are poorly developed on land.

4. A prominent air-pressure feature on this map is a belt of extremely low pressure (shown in dark gray) in the ocean just off Antarctica. This belt is so well developed in the Southern Hemisphere because of the abundant ocean surface, uninterrupted by continental landmasses at this latitude (60° S). An intense high-pressure belt (very light gray) occurs over continental Antarctica, in contrast to the oceanic Arctic.

January Air Pressure

5. Patterns of air pressure change with the seasons, following changes in insolation patterns. In January, one of the most prominent air-pressure features is a high-pressure area over Siberia, Russia, called the *Siberian High*. As discussed later, this high pressure helps drive the monsoon that affects much of southern Asia.

6. The broad belt of tropical low pressure moves toward the Southern Hemisphere, following the direct rays of the Sun (remember that January is in the southern summer). The migration is particularly noticeable over the hot land surfaces, like Australia.



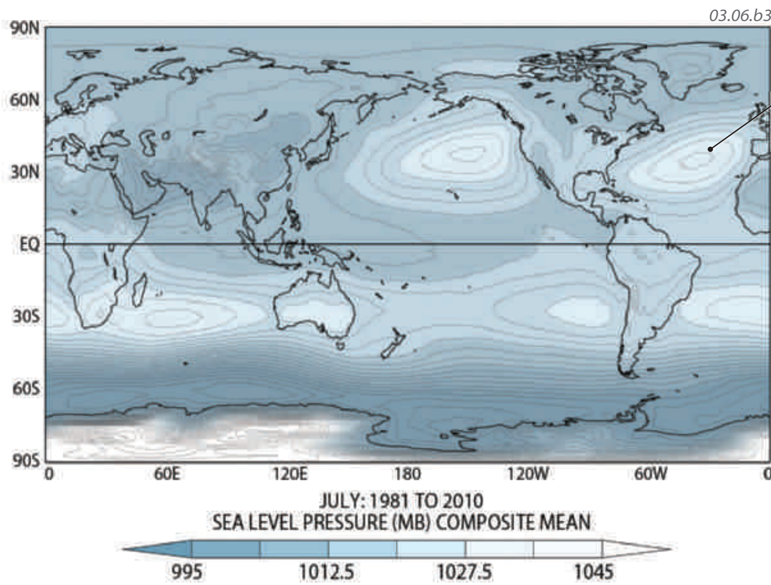
7. A large area of low pressure, called the *Icelandic Low*, develops over the northern Atlantic Ocean, wrapping around Greenland. As ocean waters retain their heat better at this cold time of year, a similar low, the *Aleutian Low*, develops in the northern Pacific Ocean west of Canada.

8. Elongated highs (shown in light gray) occur over the oceans in the Southern Hemisphere subtropics, but not over the adjacent continents. The highs are enhanced by the relatively cool oceans in this region. Farther south is the pronounced belt of low pressure in the cold oceans that encircle Antarctica.

July Air Pressure

9. Air-pressure patterns change markedly by July, the northern summer. In the Northern Hemisphere, the Siberian High has dissipated as warm air over interior Asia rises. Pressure gradients across the Northern Hemisphere are weaker in July than in January, because the equator-to-pole energy gradient isn't as steep in the summer as it is in the winter.

10. Typical patterns remain in the Southern Hemisphere, with belts of high pressure in the subtropics, flanked to the south by a continuous belt of very low pressure across the southern oceans. High pressure strengthens over the main landmass of Antarctica during the prolonged darkness of the southern winter.



11. Bullseye-shaped high-pressure areas develop over the oceans, one over the central Atlantic (the *Bermuda-Azores High*) and another in the Pacific near Hawaii (*Hawaiian High*).

Before You Leave This Page Be Able To

- ✓ Sketch and explain the global air-circulation patterns, summarizing how they differ over land versus oceans.
- ✓ Summarize the main patterns of air pressure, identifying key features.

3.7 What Is the Coriolis Effect?

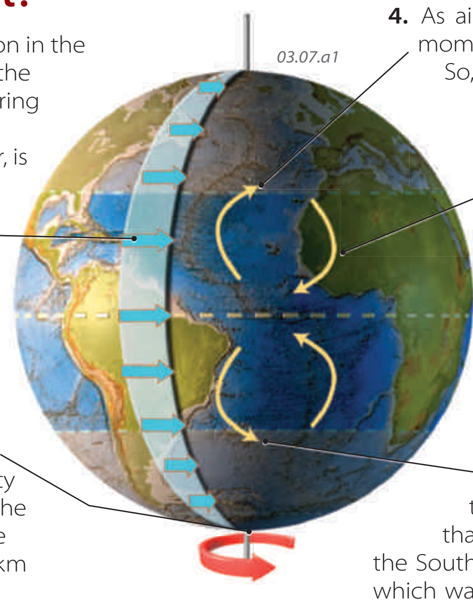
THE PRESSURE-GRADIENT FORCE drives airflow in the atmosphere, but winds do not blow in exactly the direction we would predict if we only consider pressure gradients. All objects — whether air masses, ocean waters, or airplanes — moving across the surface of the Earth display an apparent deflection from the objects' intended path. The cause of this deflection is the *Coriolis effect*. Why does this apparent deflection occur?

A What Is the Coriolis Effect?

1. The *Coriolis effect* refers to the apparent deflection in the path of a moving object in response to rotation of the Earth. The easiest way to envision this is by considering air that is moving from north to south or south to north. Earth's atmosphere, including any moving air, is being carried around the Earth by rotation.

2. The blue arrows show how much distance the surface rotates in an hour. The arrows are longer near the equator, indicating a relatively long distance that these areas have to travel, and therefore faster velocities. The distances traveled and the linear velocities gradually decrease toward the poles.

3. At the poles, the distance traveled and velocity are both zero — the surface has no sideways velocity due to the rotation. In 24 hours, an area directly at the pole would simply spin 360°, whereas an area at the equator would have moved approximately 40,000 km (the circumference of the Earth).



4. As air moves toward the poles, it possesses the eastward momentum that it had when it was closer to the equator. So, it appears, from the perspective on Earth's surface, to be deflected to the right (to the east).

5. The opposite occurs as air moves toward the equator and encounters areas with a faster surface velocity. The air appears to lag behind, deflecting to the west as if it were being left behind by Earth's rotation. Note that in the Northern Hemisphere, air deflects to the right of the flow (not necessarily to the right as you look at it on a map), irrespective of which way it is moving (toward the pole, away from the pole, or in some other direction).

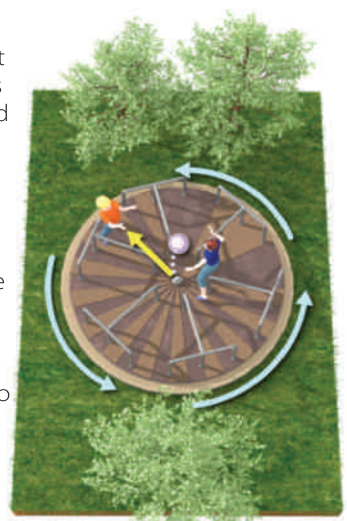
6. In the Southern Hemisphere, air moving toward the pole travels from faster rotating areas to slower ones, so it appears to be rotating faster than the surface — it deflects to the left. Moving air in the Southern Hemisphere deflects to the left irrespective of which way it is moving.

B Why Do Moving Objects Appear to Deflect Right or Left on a Rotating Planet?

To visualize why moving objects on a rotating planet appear to deflect left or right, examine these overhead views of a merry-go-round that is rotating counterclockwise (in the same way as Earth when viewed from above the North Pole). One person located at the center of the merry-go-round throws a ball to a second person standing near the outside edge of the merry-go-round. The path of the ball can be measured relative to two frames of reference: the two clumps of trees, which are fixed in our perspective, or from the persons on the merry-go-round, which is moving.

1. The person at the center of the merry-go-round slowly tosses a purple ball toward an outer person, in the direction of the upper two trees. The intended path of the ball is shown by the yellow arrow. The outer part of the merry-go-round moves faster than the center.

2. After a short time, the ball is heading toward the two trees, but, relative to the intended path (yellow arrow) or from the perspective of the thrower, the purple ball seems to be veering away to the right, because the thrower rotated.



3. With each passing time period, the intended receiver moves farther away from the ball as the ball goes toward the two trees. As viewed from the thrower, the ball deflected to the right relative to the intended path.

4. In the last figure, the ball's path traced upon the moving framework of the merry-go-round (open purple circles) reveals an apparent deflection to the right (shown with a dashed red line) of the intended path. However, relative to the fixed reference of the upper two trees, the ball has actually followed a straight line. This view is similar to one of the rotating Earth viewed from above the North Pole. The thrower and receiver are two locations at different latitudes, and the ball represents an air mass moving from the slow-moving pole toward the faster-moving equator.

C Will Deflection Occur if Objects Move Between Points on the Same Latitude?

A similar deflection occurs if an object moves parallel to latitude on a rotating planet. To visualize why this is so, we return to the merry-go-round, which is still rotating counterclockwise, like Earth viewed from above the North Pole. As before, it is key to consider movements in terms of a fixed reference frame and a reference frame that is moving.

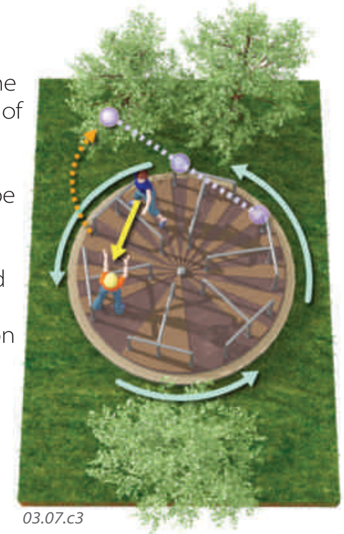
1. The person throwing the ball is on the outside of the merry-go-round along with the receiver. The intended path of the ball is shown by the yellow arrow. Since the players are the same distance out from the center, they are moving at the same rate.

03.07.c1

2. After a short time, the ball is heading along its original path (the purple path) relative to the upper two trees (the fixed reference frame). In the intervening time since the throw, however, the thrower and receiver have both moved (a moving reference frame).

03.07.c2

3. From the moving frame of reference of the thrower, the ball appears to be deflected to the right of the intended path, with the deflection shown by the orange dashed line.



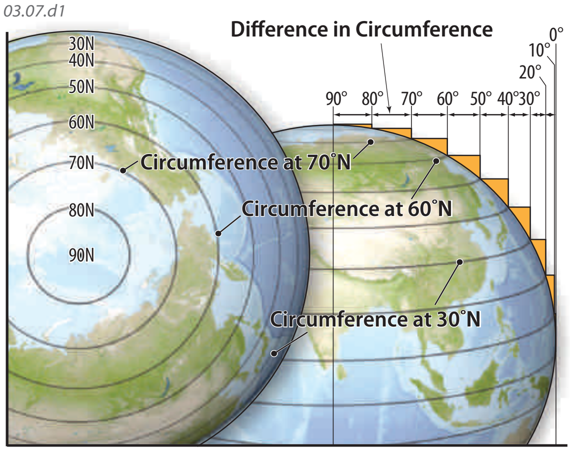
03.07.c3

4. This example represents the apparent deflection of air (or any other object) moving *parallel to latitude*. So regardless of whether objects are moving in the north-south (meridional) or the east-west (zonal) directions, the objects appear to be deflected from their intended path. Moving objects have an apparent deflection to the right of their intended path in the Northern Hemisphere and to the left in the Southern Hemisphere. This left or right deflection due to the Coriolis effect accounts for the directions of prevailing winds, the paths of storms, and the internal rotation within hurricanes.

D What Affects the Strength of the Coriolis Effect?

Since the Coriolis effect is related to the rate at which areas of the surface move during rotation of the Earth, we would suspect the strength of the effect may vary with latitude. It is also influenced by how fast objects are moving.

03.07.d1

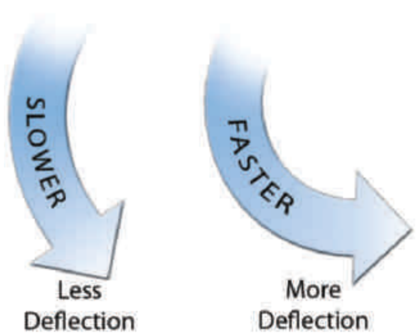


1. When viewed from above the poles, the parallels of latitude constitute a series of concentric circles increasing in circumference from the poles to the equator. Moving from one latitude to another, like from the pole to 80° N, the percentage increase in circumference is much greater at high latitudes than nearer the equator. The difference in circumference for every 10° difference in latitude is plotted as orange triangles that represent the changing "slope" of the Earth's surface. Thus, the Coriolis effect is greatest at high latitudes, where the velocity of the moving reference frame changes most rapidly relative to the moving object.

03.07.d2 Hurricane Irene 2011

2. The Coriolis effect is expressed daily in many ways, including the shape of storms as viewed by satellites and featured on the daily weather report, the rotation of hurricanes (◀), and the changes in wind directions as a large storm approaches and then exits your town.

3. The Coriolis effect is stronger for an object with a large amount of mass, like a huge storm, or for an object that is accelerating (moving faster with time). In the case of a rotating storm, the acceleration can be related to movement of the entire storm across Earth's surface, rotations within the storm, and other motions. In any case, the Coriolis effect deflects faster moving objects more than it does slower moving objects.



03.07.d3

Before You Leave This Page Be Able To

- ✓ Explain what the Coriolis effect is and the direction of apparent deflection of moving objects in the Northern and Southern Hemispheres.
- ✓ Explain why a moving object on a rotating reference frame shows an apparent deflection.
- ✓ Explain what controls the strength of the Coriolis effect.

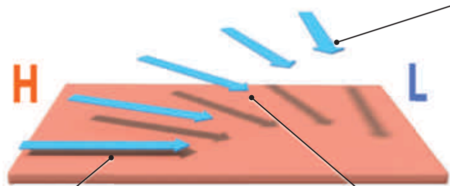
3.8 How Does the Coriolis Effect Influence Wind Direction at Different Heights?

PRESSURE GRADIENTS INITIATE MOTION in the atmosphere, but the actual direction in which the air moves is greatly influenced by the Coriolis effect. Close to the surface, where friction with the planetary surface is greatest and wind velocities are lowest, the pressure gradient dominates. Higher in the atmosphere, winds have higher velocities and the Coriolis effect dominates. The resulting patterns of airflow can dominate weather systems.

A Why Do Wind Speed and Direction Change with Height near the Surface?

The direction in which air moves is determined by three factors: 1) the pressure-gradient force (winds blow from higher pressure toward lower pressure); 2) the Coriolis effect, which appears to deflect objects moving across Earth's surface, and 3) friction with Earth's surface, which cannot change direction by itself but can interact with the other two forces to change the speed and direction of wind. Friction becomes less important upward.

1. This figure shows how wind direction can change upward, from the surface to well above the friction layer. Winds are fastest higher up and progressively slower down closer to the surface. This example is in the Northern Hemisphere.



03.08.a1

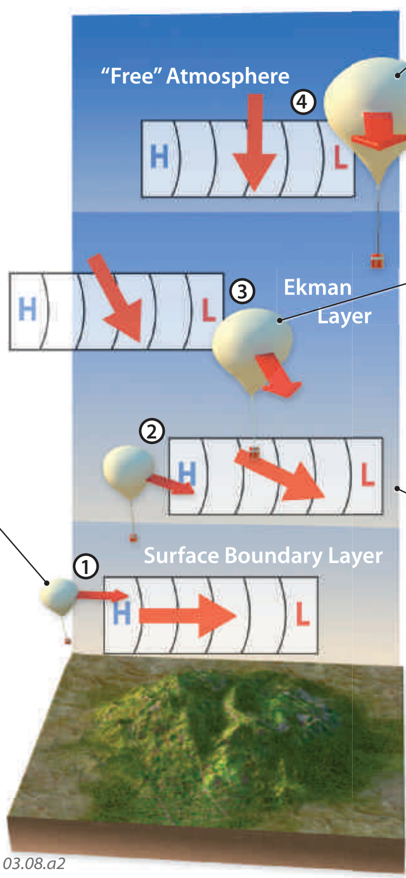
2. The pressure-gradient force, caused by the pressure gradient between a high (H) and a low (L), causes winds right above the surface to blow from higher pressure to lower pressure, in an attempt to even out the pressure gradient. Even though friction is strong near the surface, it merely slows the wind; it does not by itself change the wind's direction.

3. Higher up, friction is decreased, so winds are stronger. Since the Coriolis effect is proportional to wind speed, it begins deflecting air to the right (or to the left in the Southern Hemisphere). This causes successively more and more deflection with height.

4. At some height, the deflection will be such that the winds flow parallel to the pressure gradient—no longer from higher to lower pressure. Further turning cannot happen because if it did, the flow would be going against the pressure gradient, from lower pressure toward higher pressure. The height at which this flow neither toward nor away from lower pressure (i.e., parallel to isobars) occurs is called the *geostrophic level*. It typically occurs when air pressure is about half that at the surface (i.e., the 500 mb level).

5. To illustrate how wind direction can change with altitude, examine what commonly happens to a balloon as it ascends from the surface. The red arrows indicate wind direction and the inset maps show isobars between high- and low-pressure areas. Follow the balloon's progress from the surface upward, starting with the text below.

6. Right after the balloon takes off, in Position 1 on this figure, the pressure-gradient force and friction are the primary factors that affect wind speed. The balloon will go from higher pressure to lower pressure, across the pressure gradient as it rises. Friction slows the circulation in this lowest part of the friction layer, which is called the *surface boundary layer*.



03.08.a2

9. Eventually, the balloon will ascend to a height (1–2 km above the surface) at which friction becomes negligible (above the *friction layer*). At that point, only the pressure-gradient force and the Coriolis effect are important in dictating flow. The wind speed is faster because of the reduced friction, so the Coriolis effect continues to pull the balloon to the right until it no longer flows toward lower pressure. Instead, the wind is perpendicular to the pressure-gradient force and parallel to isobars. This type of wind, flowing parallel to the isobars, is called a *geostrophic wind*.

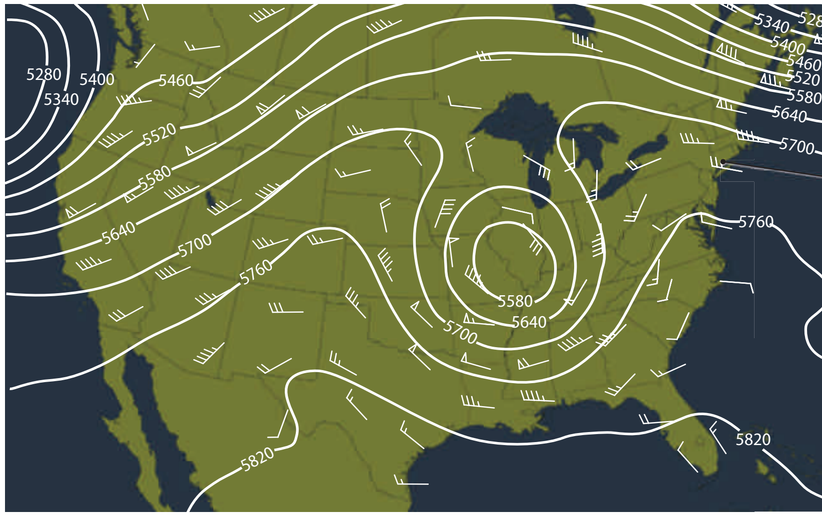
8. As the balloon continues to rise, near Position 3, it experiences less and less friction, so the winds strengthen with height. This makes the Coriolis deflection even stronger with increasing height. The winds and the balloon move even less from higher pressure to lower pressure, instead turning at an angle to the isobars. This layer characterized by a turning of the winds with height (shown in Positions 2 and 3) is called the *Ekman layer*. It exists from about 100 m to about 1–2 km above the surface. The Ekman layer is a part of the friction layer.

7. In Position 2, the balloon has risen high enough from the surface that friction becomes weaker. This weakening of friction speeds up the balloon, and it also increases the impact of the Coriolis effect, because faster winds cause an increasing rightward deflection. This causes the balloon to move somewhat to the right of the direction that the pressure-gradient force would otherwise take it. The balloon therefore begins to travel more to the right as it rises.

03.08.a3 Namibia

B How Do We Depict Upper-Level Wind Patterns?

1. This map shows another way to represent pressure in the atmosphere, by contouring the height (in meters) at which 500 mb of pressure is reached. The contour lines represent lines of constant height and are called *isohypses*. Surface pressure is about 1000 mb, so the 500 mb level represents the height bounding the lower half of the atmospheric mass. This height is also generally considered to be the lowest level at which geostrophic winds occur. The higher the 500 mb level occurs, the higher the pressure. These "constant pressure surface maps" are used by the National Weather Service and other organizations in making weather maps, because of the need for constant pressure surfaces in the aviation industry.



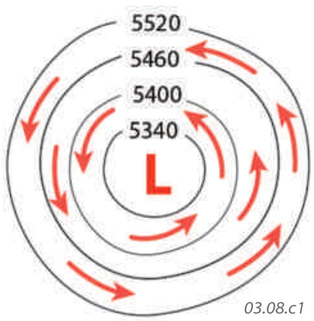
03.08.b1

2. This map also has symbols, called *wind barbs*, that show the direction and velocity from which the wind is blowing. The barb is parallel to wind direction, and each flag on the barb represents 50 knot (kt) winds (two flags indicate winds of 100 knots). Each full hash mark designates 10 kt, and each half-barb represents 5 kt. The wind barbs on this map show that winds generally flow parallel to the isohypses (they are geostrophic).

C Which Way Does Air Flow Around Enclosed High- and Low-Pressure Areas Aloft?

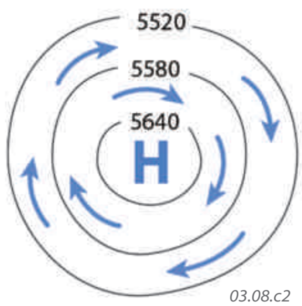
Aloft, in upper parts of the troposphere, well above the friction layer, wind directions are dominated by the Coriolis effect and so are typically geostrophic. As a result, air circulation can be nearly circular around upper-level lows and highs. In situations in which the flow is nearly circular, the low or high pressure typically lasts for a longer period of time than in cases where the flow is not enclosed as tightly, such as in an upper level *ridge* or *trough* of pressure. Closed circulations at the 500 mb level or above suggest a strong circulation that is not likely to dissipate soon. The figures below are map views.

Northern Hemisphere



03.08.c1

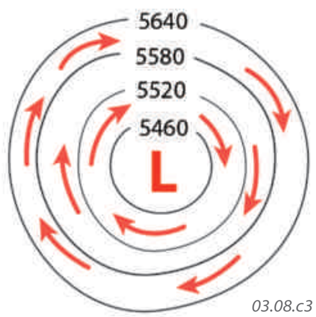
For low pressure, the pressure-gradient force pushes air into the low from all directions, but at high altitudes the Coriolis effect deflects this air until it parallels the isohypses. In the Northern Hemisphere, the deflection into a low is to the right, so the upper-level flow goes *counterclockwise* around the enclosed low-pressure area. This type of curved flow is called *gradient flow*.



03.08.c2

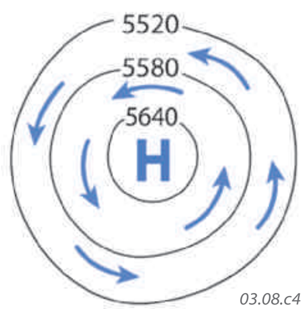
For a high-pressure area, the pressure-gradient force pushes air out of the high in all directions, but the Coriolis effect deflects winds to the right, parallel to the isohypses. Due to this deflection, the gradient flow goes *clockwise* around the high-pressure area.

Southern Hemisphere



03.08.c3

Similar processes occur around lows in the Southern Hemisphere. Air pushed into the low from all directions is deflected to the left by the Coriolis effect, until it flows parallel to the isohypses. The gradient flow therefore goes *clockwise* around a low in the Southern Hemisphere.



03.08.c4

In the Southern Hemisphere, deflection of air moving out from a high is to the left, causing the gradient flow to be counterclockwise around a high. In both hemispheres, pressure gradients tend to be weaker around highs, which are typically associated with fair weather, than around lows, which are commonly associated with stormy and windy weather.

Before You Leave This Page Be Able To

- ✓ Sketch and explain why wind directions change from the surface to higher levels in the troposphere.
- ✓ Explain what a geostrophic wind is and how you would recognize one on a map that represents air pressure.
- ✓ Sketch the upper-level flow around low-pressure and high-pressure areas in both the Northern and Southern Hemispheres.

3.8

3.9 How Do the Coriolis Effect and Friction Influence Atmospheric Circulation?

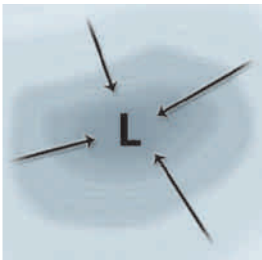
THE CORIOLIS EFFECT AND FRICTION affect the patterns of air movement set in motion by pressure gradients. These phenomena influence wind direction from local scales, affecting the rotation and wind patterns of individual storms, to global scales, affecting wind patterns of the entire planet. How do pressure gradients, the Coriolis effect, and friction explain wind patterns at such diverse scales? These two pages provide an overview of global and regional patterns of air circulation, with more in-depth coverage to follow in subsequent sections.

A What Influences the Patterns of Airflow Around High- and Low-Pressure Areas?

Once the pressure-gradient force starts air moving, the air is affected by the Coriolis effect and, if close to Earth's surface, is acted on by friction with the surface. The results of these interactions produce distinctive and familiar patterns of wind and circulation of air around areas of high and low pressure.

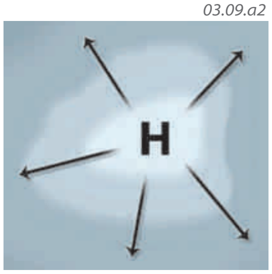
Low- and High-Pressure Areas

03.09.a1



1. In an area of *low pressure*, the pressure-gradient force pushes air laterally into the low from all directions. If the Earth were not rotating and therefore had no Coriolis effect, this simple inward flow pattern would remain intact. Friction would likewise not perturb this pattern because friction does not change the direction of airflow, only the speed.

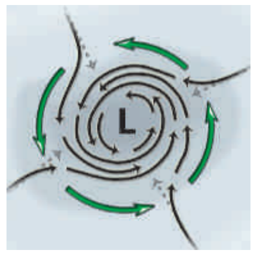
03.09.a2



2. In an area of *high pressure*, the pressure-gradient force pushes air laterally out in all directions. As with a low pressure, this outward flow of air is influenced by the Coriolis effect and by friction near Earth's surface. As air flows outward from the high, it is replaced by air flowing down from higher in the atmosphere.

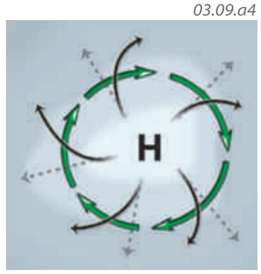
Northern Hemisphere

03.09.a3



3. Earth does rotate, so the Coriolis effect, represented in this figure by green arrows, deflects the inward-flowing air associated with a low-pressure area. This deflection causes an inward-spiraling rotation pattern called a *cyclone*. In the Northern Hemisphere, the Coriolis deflection is to the right of its intended path, causing a *counterclockwise* rotation of air around the low-pressure zone. This counterclockwise rotation is evident in Northern Hemisphere storms.

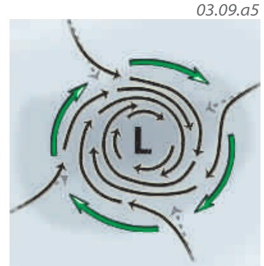
03.09.a4



4. In a Northern Hemisphere high-pressure area, the Coriolis effect deflects winds to the right, but friction again slows the winds. This results in an outward-spiraling rotation pattern called an *anticyclone*. In the Northern Hemisphere, circulation around an anticyclone is *clockwise* around the high-pressure zone.

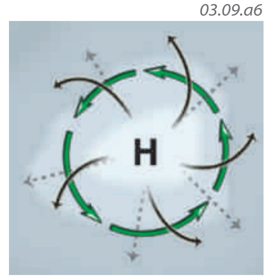
Southern Hemisphere

03.09.a5



5. For a low-pressure area in the Southern Hemisphere, the air flowing inward toward a low is deflected to the left by the Coriolis effect. This causes air within a cyclone in the Southern Hemisphere to rotate *clockwise*, opposite to what is observed in the Northern Hemisphere. In either hemisphere, friction causes wind patterns within cyclones to be intermediate between straight-inward winds and circular gradient winds.

03.09.a6



6. For a high in the Southern Hemisphere, the air flowing outward from the high is deflected to the left by the Coriolis effect. This causes the air within an anticyclone in the Southern Hemisphere to rotate *counterclockwise*, opposite to the pattern in the Northern Hemisphere. Therefore, cyclones and anticyclones can rotate either clockwise or counterclockwise, depending on hemisphere.

03.09.a7

7. This satellite image (◀) shows a cyclone near Iceland (Northern Hemisphere). It is characterized by a circular rotation of strong winds around the innermost part of the storm. It displays a distinctive inward-spiraling flow of the clouds and air around an area of low air pressure. Within a cyclone, air moves rapidly down the pressure gradient toward the very low pressure at the center of the storm. In the Northern Hemisphere, the air is deflected to the right of its intended path, resulting in an overall counterclockwise rotation of the storm. The distinctive spiral pattern results from a combination of the pressure-gradient force (which started the air moving), the Coriolis effect, and friction with Earth's surface. A hurricane, which is a huge tropical cyclone, shows a similar pattern of rotation around the center of the storm — the eye of the hurricane.

B What Factors Influence Global Wind Patterns?

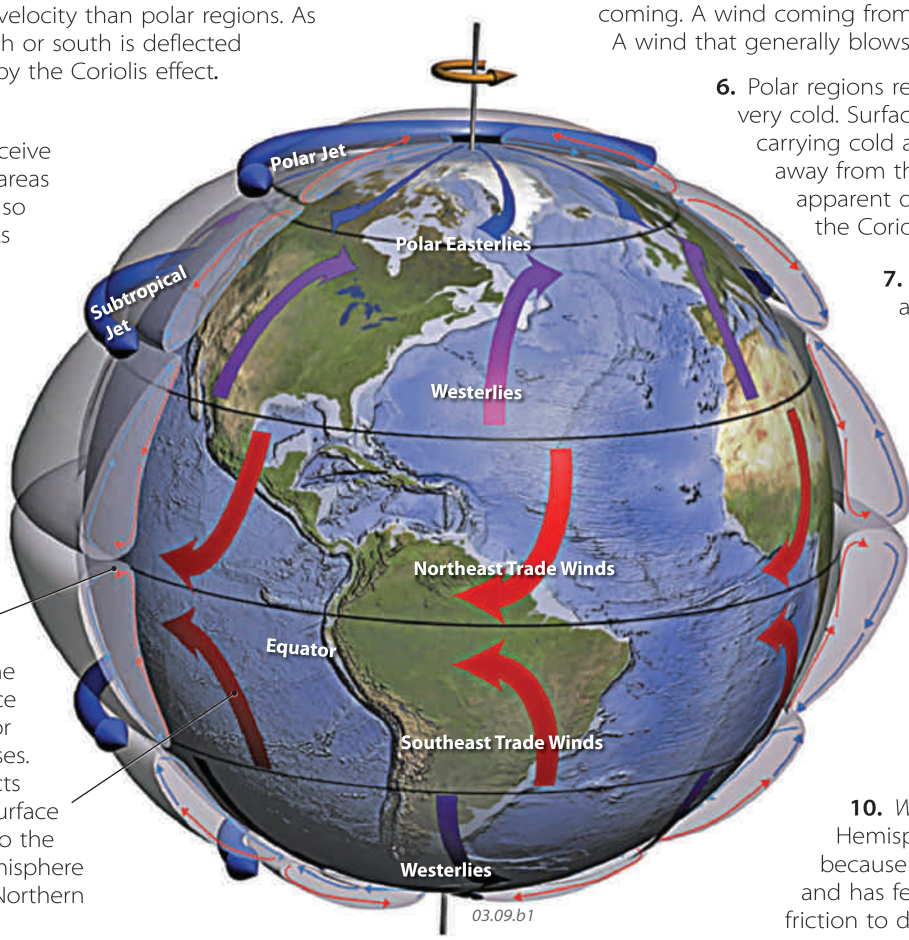
Insolation warms equatorial regions more than the poles, setting up pressure differences that drive large-scale atmospheric motion. Once set in motion, the moving air is acted upon by the Coriolis effect and by friction with Earth's surface. These factors combine to produce curving patterns of circulating wind that dominate wind directions, climate, and weather.

Rotation and Deflection

1. Earth is a spinning globe, with the equatorial region having a higher velocity than polar regions. As a result, air moving north or south is deflected from its intended path by the Coriolis effect.

2. Equatorial regions receive more sunlight than do areas closer to the poles and so preferentially heat up. As Earth rotates, the Sun's heat forms a band of warm air that encircles the globe and is re-energized by sunlight each day.

3. Warmed equatorial air rises and flows north and south, away from the equator. Air at the surface flows toward the equator to replace the air that rises. The Coriolis effect deflects this equatorial-flowing surface wind toward the west (to the left in the Southern Hemisphere and to the right in the Northern Hemisphere).



4. These flows of air combine into huge, tube-shaped cells of circulating winds, called *circulation cells*. Very fast flows of air along the boundaries of some circulation cells are *jet streams*.

Prevailing Winds

5. Wind direction is referenced by the direction from which it is coming. A wind coming from the west is said to be a "west wind." A wind that generally blows from the west is a *westerly*.

6. Polar regions receive the least solar heating and are very cold. Surface winds move away from the poles, carrying cold air with them. *Polar easterlies* blow away from the North Pole and have a large apparent deflection toward the west because the Coriolis effect is strong at high latitudes.

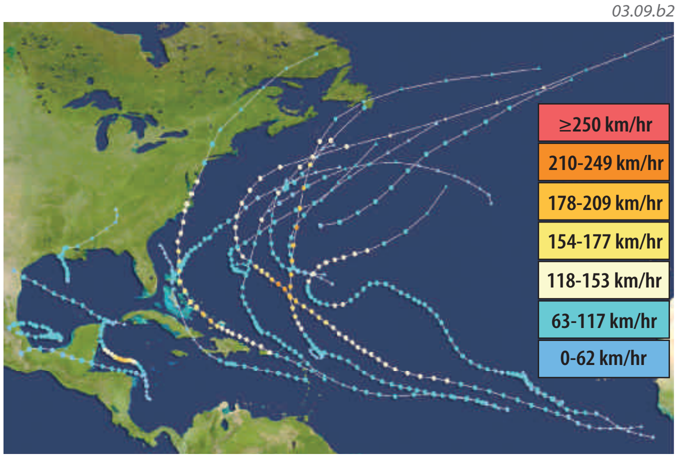
7. *Westerlies* dominate a central belt across the U.S. and Europe, so weather in these areas generally moves from west to east.

8. *Northeast trade winds* blow from the northeast and were named by sailors, who took advantage of the winds to sail from the so-called Old World to the New World.

9. *Southeast trade winds* blow from the southeast toward the equator. Near the equator, they meet the northeast trade winds in a stormy boundary called the *Intertropical Convergence Zone (ITCZ)*.

10. *Westerlies* also occur in the Southern Hemisphere and are locally very strong because this belt is mostly over the oceans and has few continents to generate additional friction to disrupt the winds.

11. *Polar easterlies* flow away from the South Pole and deflect toward the west but are mostly on the back side of the globe in this view. The Coriolis effect causes this large apparent deflection due to the very high latitudes.



12. The origins and paths of hurricanes in the North Atlantic and Caribbean basins in 2011 are shown here (◀). Note that few storms originate in the far southern part of this map, partly because the Coriolis effect is so small at these latitudes that it fails to impart the necessary rotation to the storms. Once formed, the paths of hurricanes are steered by the global wind patterns, which generally move Atlantic hurricanes west (guided by the trade winds) and then north and east once they enter the latitudes of the westerlies.

Before You Leave This Page Be Able To

- ✓ Sketch, label, and explain the combined effect of the pressure-gradient force, Coriolis effect, and friction, and how this is expressed in flow around anticyclones and cyclones in both the Northern and Southern Hemispheres.
- ✓ Locate and name on a map the main belts of global winds.

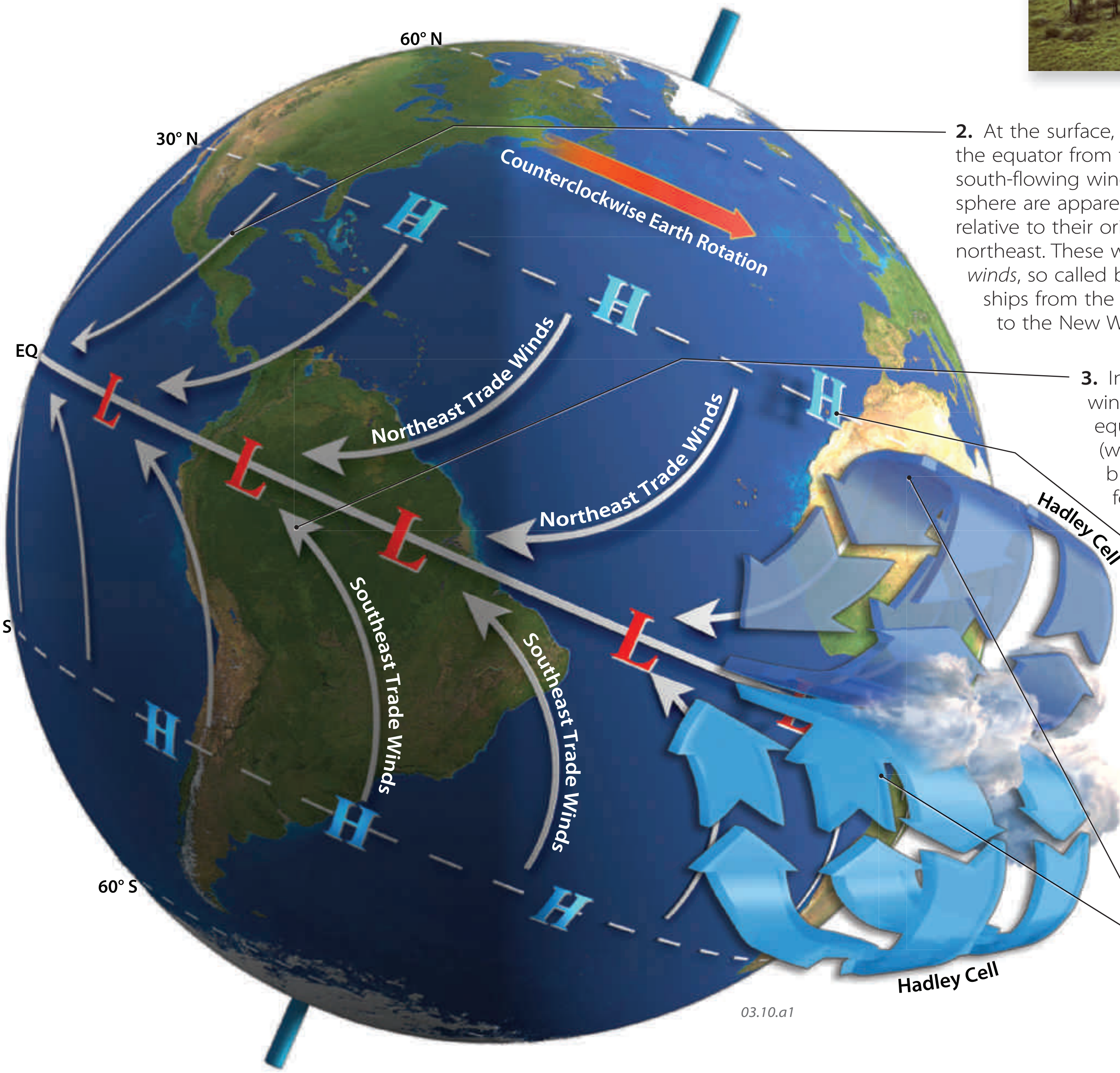
3.10 How Does Air Circulate in the Tropics?

TROPICAL CIRCULATION is driven by the intense solar heating of land and seas near the equator. The heated air rises and spreads out from the equator, setting up huge, recirculating cells of flowing air. The rising air results in a belt of tropical low pressure, and where the air descends back toward the surface is a belt of subtropical high pressure. What determines where the rising and sinking occur, and how does the Coriolis effect influence this flow?

General Circulation in the Tropics

1. Examine the large figure below and note the main features. What do you observe, and can you explain most of these features using concepts you learned from previous parts of the chapter? Tropical areas are known for their lush vegetation (▶), which in turn is due largely to relatively abundant and consistent insolation, warm temperatures, and abundant rainfall. After thinking about these aspects, read the rest of the text.

03.10.a2 Kakadu World Heritage Site, Australia



03.10.a1

2. At the surface, winds generally converge on the equator from the north and south. The south-flowing winds in the Northern Hemisphere are apparently deflected to the right relative to their original path, blowing from the northeast. These winds are the *northeast trade winds*, so called because they guided sailing ships from the Old World (Europe and Africa) to the New World (the Americas).

3. In the Southern Hemisphere, winds blowing toward the equator are deflected to the left (west), resulting in winds blowing from the southeast, forming the *southeast trade winds*.

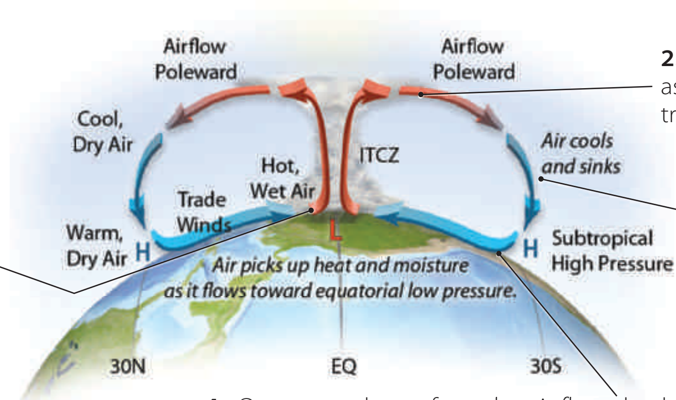
4. A belt of high pressure occurs near 30° N and 30° S, where air descends to the surface of the Earth. This air rose in the low pressure located near the equator, as a result of excess heating.

5. The rising and descending air, and the related high- and low-pressure areas, are linked together in a huge cell of convecting air—the *Hadley cell*. One Hadley cell occurs north of the equator and another just south of the equator.

6. Note that the Hadley cell extends to approximately 30° north and south of the equator, so it generally encompasses all the tropics and some distance beyond.

Formation of Hadley Cells

1. Insolation, on average, is most intense near the equator, in the tropics. The position of the overhead Sun migrates between the Tropic of Cancer and Tropic of Capricorn from season to season. The Sun-heated air rises from the tropics, forming a belt of low pressure at the surface. As the warm, moist air rises, the air cools somewhat, forming clouds; this accounts for the typical cloudiness and haziness of many tropical areas.



03.10.a3

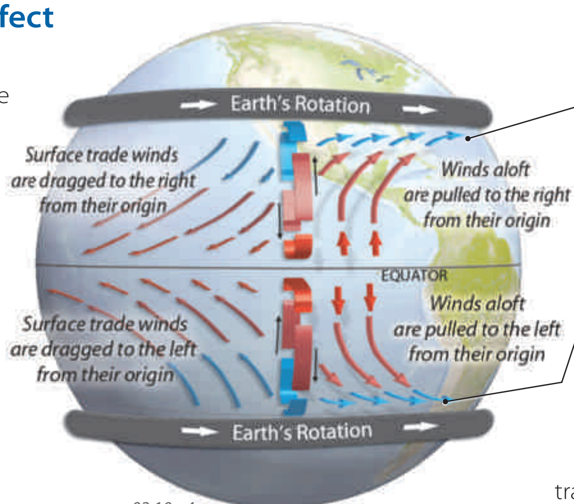
2. After rising, this air spreads out poleward as it approaches the upper boundary of the troposphere (the tropopause).

3. Once the upper-level flow reaches about 30° N and 30° S latitude, it sinks, both because it begins to cool aloft and due to forces arising from the Earth's rotation. This sinking air dynamically compresses itself and the surrounding air, producing the subtropical high-pressure systems.

4. Once near the surface, the air flows back toward the equator to replace the air that rose. The flow from the two hemispheres converges at the ITCZ.

Influence of the Coriolis Effect

5. As the air flows toward the equator in each hemisphere from the subtropical high to the ITCZ, the Coriolis effect pulls it to the right of its intended path (in the Northern Hemisphere) or left (in the Southern Hemisphere), as shown by the arrows on the left side of this diagram. The Coriolis effect is weak near the equator, however, so the deflection is only slight. The result is surface air flowing from northeast to southwest in the Northern-Hemisphere tropics (the northeast trade winds) and from southeast to northwest in the Southern-Hemisphere tropics (the southeast trade winds).



03.10.a4

6. In the Northern Hemisphere, as the air flows poleward after rising at the ITCZ, the weak Coriolis effect also pulls the air slightly to the right of its intended path. The result is that some of the upper-level air moves from southwest to northeast at the top of the Northern Hemisphere Hadley cell.

7. In the Southern Hemisphere, the Coriolis effect deflects the upper-level winds to the left of their intended path, causing a northwest-to-southeast flow at the top of the Southern Hemisphere Hadley cell.

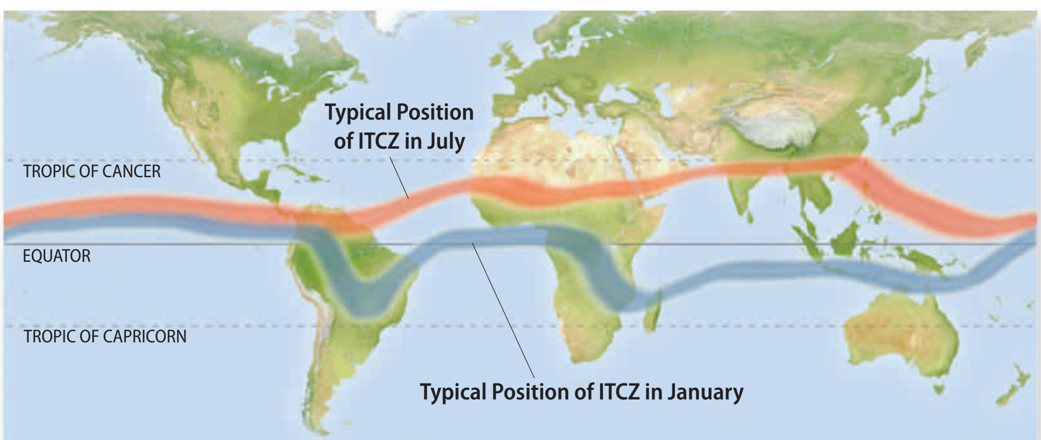
8. As the seasons progress, the set of Hadley cells and the ITCZ migrate—to the Northern Hemisphere in Northern-Hemisphere summer and to the Southern Hemisphere in Southern-Hemisphere summer. If the trade-wind flow crosses the equator, the Coriolis deflection begins to occur in the opposite direction, and the winds can reverse direction (not shown).

Seasonal Variations in the Position of the Intertropical Convergence Zone

9. As the overhead Sun shifts north and south within the tropics from season to season, the ITCZ shifts, too. In the northern summer, it shifts to the north. The typical June position of the ITCZ is the red line on the figure below, and the December position is the blue line.

10. The ITCZ generally extends poleward over large landmasses in the hemisphere that is experiencing summer. This larger shift over the land than over the oceans is because of the more intense heating of land surfaces.

11. Unlike the ITCZ, the subtropical high pressure doesn't exist in a continuous belt around the Earth. The ocean-covered surfaces support high pressure better than land surfaces because land heats up too much at these latitudes, especially in summer. The heated air over the land rises, counteracting the tendency for sinking air in the Hadley cell. So the subtropical high pressure tends to be more vigorous over the oceans.



03.10.a5

Before You Leave This Page Be Able To

- ✓ Sketch, label, and explain the main patterns of air circulation and air pressure over the tropics and subtropics.
- ✓ Sketch and explain air circulation in the Hadley cells.
- ✓ Describe the Intertropical Convergence Zone and its shifts.

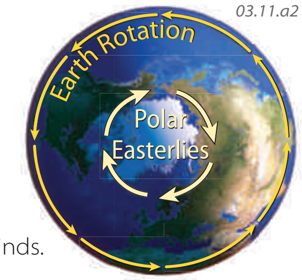
3.11 How Does Air Circulate in High Latitudes?

POLAR REGIONS RECEIVE LITTLE INSOLATION compared to the rest of Earth. As a result, the poles are very cold places, which experience winter darkness for months at a time. Air circulation around the poles reflects this relative lack of solar heating and also the proximity to the axis of rotation for the planet. The encroachment of polar air away from the poles can cause nearby areas to experience very cold temperatures. Airflow away from the poles results in a belt of relatively stormy weather near 45° to 60° N and 45° to 60° S.

General Circulation at High Latitudes

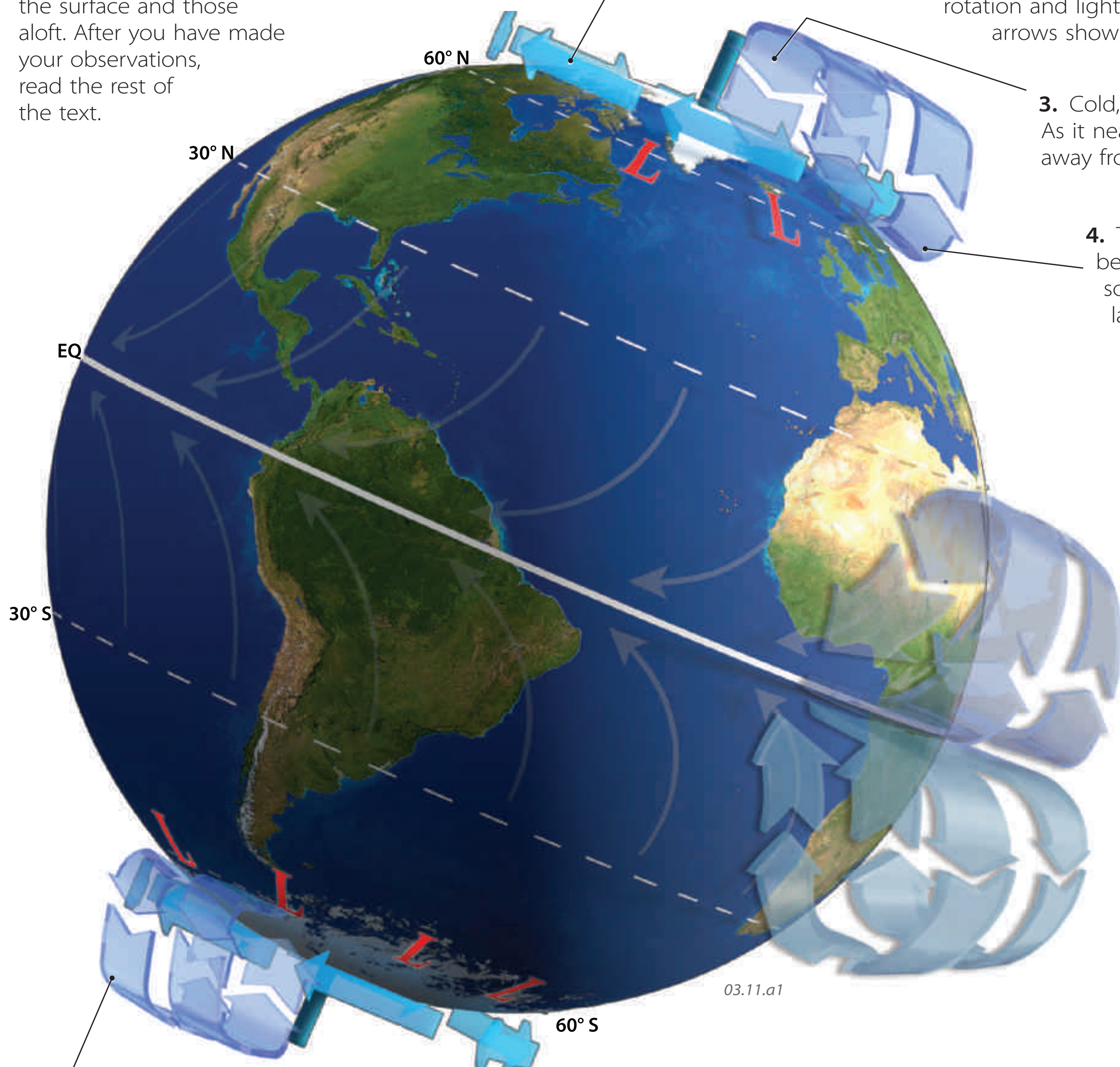
1. Examine the large figure below and observe the main features near the poles. Note the circulation directions near the surface and those aloft. After you have made your observations, read the rest of the text.

2. At the surface, winds generally encircle the North Pole, blowing in a clockwise direction when viewed from above the pole. This circulation is driven by the Coriolis effect, which is very strong at these latitudes. A north-polar view of the rotation of the Earth is shown here (▶), where golden arrows show Earth's rotation and light-yellow arrows show surface winds.



3. Cold, dense air sinks near the North Pole. As it nears the surface, it then flows outward, away from the poles (to the south).

4. The south-flowing air eventually begins to heat up and rise, usually somewhere between 60° and 45° latitude. This rising air causes a series of low-pressure areas at the surface, called the *subpolar lows* (L on this figure). Once the air rises to its maximum height, the flow turns back to the north, completing a circulating cell of cold air — the *polar cell*.



5. A similar situation occurs around the South Pole, where surface air circulates around the pole, but in a counter-clockwise direction when viewed from below the South Pole. These circular winds from the east, *polar easterlies*, are in response to the Coriolis effect, which is in turn caused by rotation of the Earth and enhanced by the comparative lack of surface friction with the ocean surfaces that dominate these latitudes.

6. As near the North Pole, cold air flowing away from the South Pole eventually heats up enough to rise, producing a belt of low pressure. The rising air aloft turns south and descends back near the pole, completing the polar cell. The polar cell involves very cold air at such high latitudes, causing the land to largely be covered year-round in ice and snow (▶).

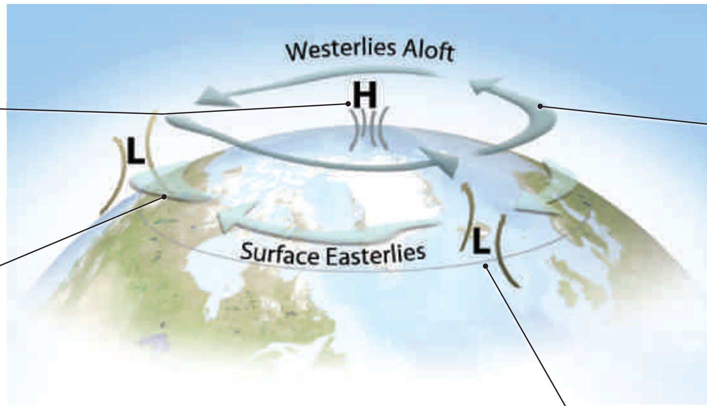
03.11.a4 Icebergs off the Antarctic Peninsula, Antarctica

Circulation Around the Poles

1. The very cold air over the poles is so dense that it has a tendency to sink vigorously to the surface, creating high surface pressure—*polar highs*. The air then moves equatorward, because that is the only direction it can go from the pole.

2. The Coriolis effect is very strong at high latitudes, so the air deflects strongly and circulates around the pole, as shown here for the North Pole. Around the North Pole, the surface winds moving south deflect to the right of their intended path and so blow from the east—they are *polar easterlies*.

03.11.a5



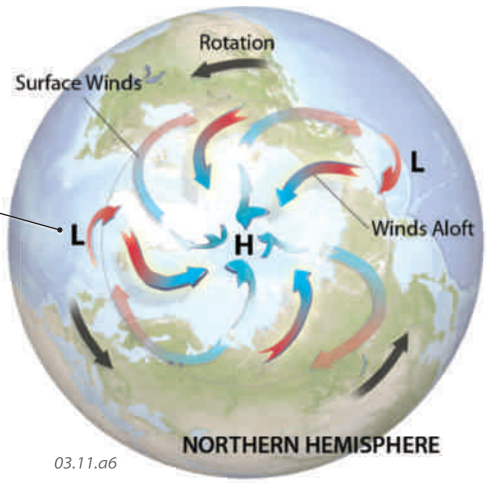
4. At upper levels, the return flow of air northward toward the pole is also deflected to the right of its intended path (in the Northern Hemisphere). As it is turned to the right, it blows from the west (a westerly flow aloft). So not only is air flowing away from the pole near the surface and toward the pole aloft, the surface and upper-level airflows are rotating in opposite directions (clockwise near the surface, counterclockwise aloft). This is difficult to capture in a single perspective, which is why the polar flow is represented on this page with several figures.

3. As the air flows away from the pole, it warms and rises, producing low surface pressure—subpolar lows. In the winter, the subpolar lows are particularly intense over water bodies because the water is relatively warm at that time of year, relative to air elsewhere at these latitudes. The water warms the air, allowing it to rise.

Northern Hemisphere

5. The figure below shows the Northern Hemisphere polar cell, as viewed directly down on the North Pole. The slightly faded arrows depict surface flows (easterlies), whereas the brighter arrows show upper-level flow (westerlies). Color gradations on arrows indicate whether air is warming (blue to red from tail to head) or cooling (red to blue).

6. High surface pressure is present at the pole, but shifts slightly in position from season to season. Low-pressure zones (the subpolar lows) occur over the adjacent oceans. The subpolar low in the Atlantic is the *Icelandic Low*. Another subpolar low, on the opposite side of the North Pole, occurs over the northern Pacific Ocean, and is the *Aleutian Low*, named for the Aleutian Islands west of mainland Alaska.

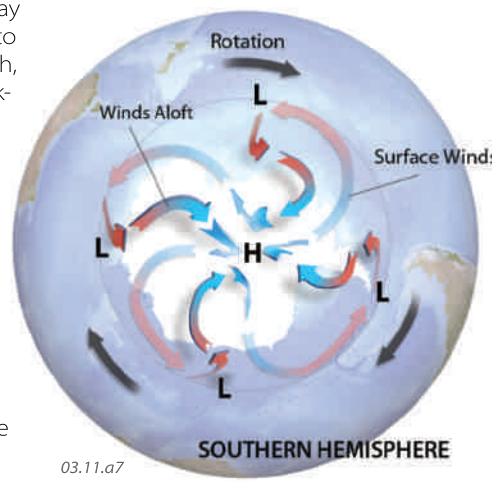


03.11.a6

Southern Hemisphere

7. The polar cell in the Southern Hemisphere, shown below, is over the South Pole. Unlike the polar cell in the Northern Hemisphere, this one is centered over land—Antarctica. Antarctica is surrounded by uninterrupted oceans. As before, faded arrows show surface flow and brighter ones show airflow aloft. The entire region is a very cold place, so even the air that is shown as warming is still very cold.

8. Surface winds flowing away from the pole are deflected to the left of their intended path, and so circulate counterclockwise around the pole when viewed from below (polar easterlies). Winds aloft move toward the pole and are deflected left of their intended path, flowing clockwise, in the opposite direction from the surface winds. The outward flowing surface air is balanced by the inward flowing air aloft. Low-pressure areas occur over the ocean.



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Differences Between the North and South Polar Areas

The general patterns of atmospheric flow are similar for the North and South polar regions, except for the reversed directions of circulation (clockwise versus counterclockwise) related to different deflection directions for the Coriolis effect in the Northern and Southern Hemispheres. One striking difference, however, is the difference between the land-sea distributions around the two poles. The North Pole is over ocean, although this ocean (the Arctic Ocean) is mostly frozen most of the year. The Arctic Ocean is nearly enclosed by the surrounding continents.

In contrast, the South Pole is over land, the frozen continent of Antarctica, and this continent is completely surrounded by open ocean. Differences in the responses of land and water to warming, cooling, and latent heat account for some difference in the specifics, such as having two main low-pressure areas in the oceans adjacent to the north polar region, but a continuous belt of low pressure in the ocean around Antarctica.

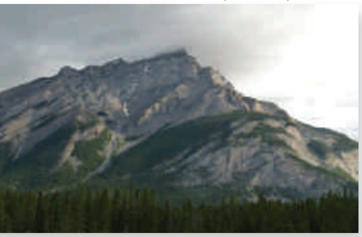
Before You Leave This Page Be Able To

- ✓ Sketch, label, and explain the main patterns of air circulation and air pressure in the polar regions.
- ✓ Sketch and explain the polar cells, summarizing why circulation occurs.
- ✓ Explain the differences between polar circulation and pressures in Northern and Southern Hemisphere.

3.12 How Does Surface Air Circulate in Mid-Latitudes?

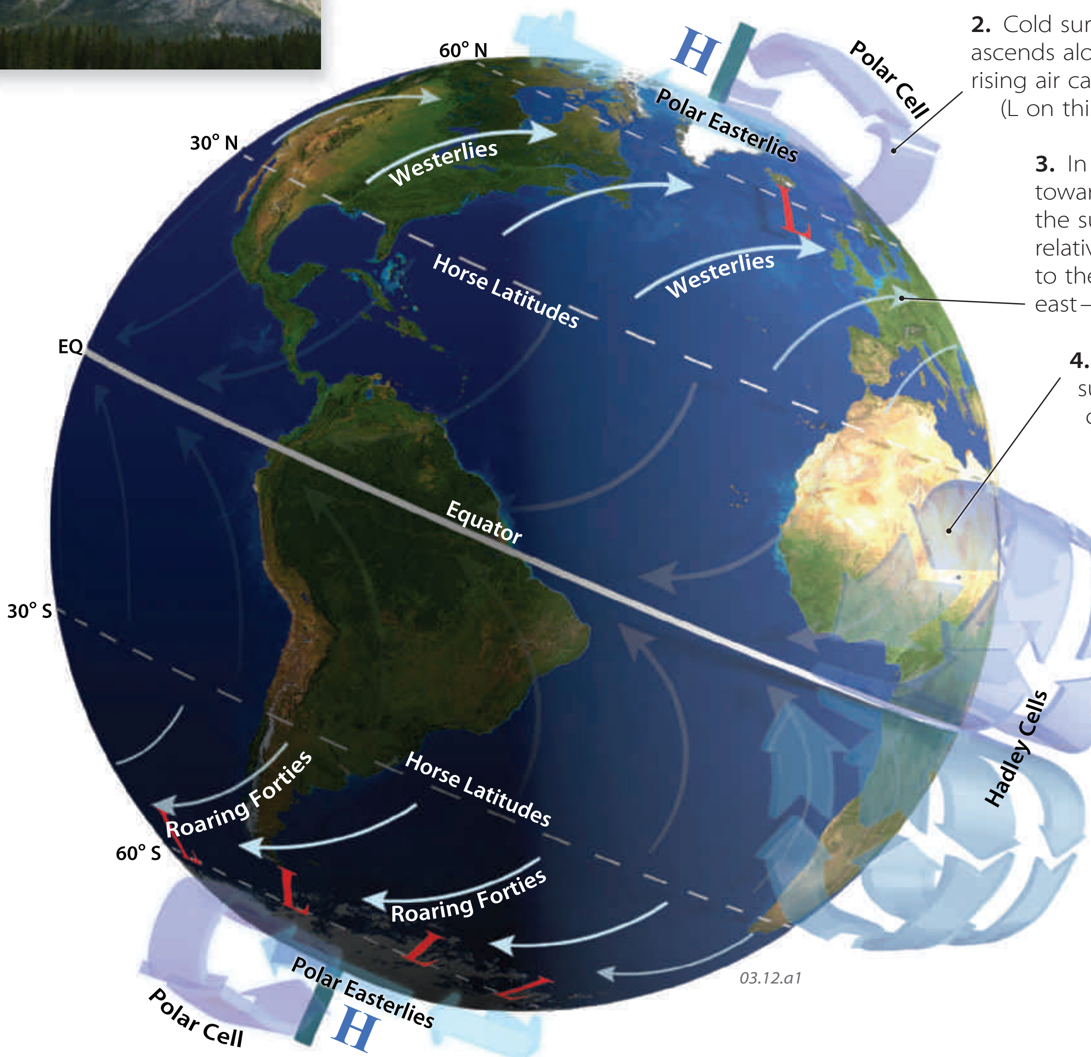
THE MID-LATITUDES are regions, in the Northern Hemisphere and Southern Hemisphere, that lie between the tropics (23.5°) and polar circles (66.5°). Air circulation in the mid-latitudes is driven by pressures set up by circulation in the adjacent tropics and polar regions, and by the Coriolis effect. Surface winds within most of the mid-latitudes blow from west to east (westerlies), but the subtropics can have a relative lack of wind.

03.12.a2 Banff, Alberta, Canada



General Circulation at Mid-Latitudes

1. Examine the large figure below and observe the main features in the mid-latitudes, especially the region between 30° and 60° latitude (the dashed lines) in both the Northern and Southern Hemispheres. The mid-latitudes are characterized by distinct seasons and changing weather patterns, and from forested areas (◀) to deserts. After observing the features on the large globe and reflecting on implications for weather, read the rest of the text.

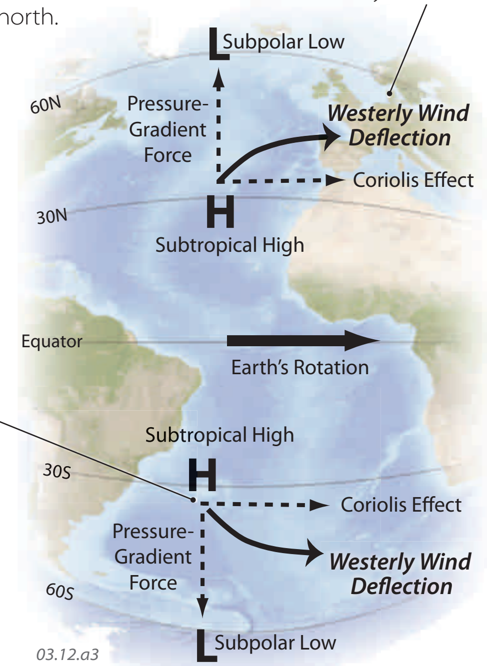


2. Cold surface air flowing away from the poles warms and ascends along the poleward edge of the mid-latitudes. This rising air causes storminess and low pressure: the *subpolar lows* (L on this figure). This rising air is part of the cold *polar cell.*

3. In the Northern Hemisphere, air from the south flows toward the subpolar lows and away from high pressure in the subtropics (near 30–35° latitude). The Coriolis effect is relatively strong in the mid-latitudes and deflects this flow to the right, forming a belt of wind blowing from west to east—the *westerlies.*

4. Along the edge of the mid-latitudes, in the subtropics, air in the descending limb of the Hadley cell causes high pressure. These regions near 30° N and 30° S—the *horse latitudes*—can have weeks without wind, which posed a hazard to early sailing ships and their cargo.

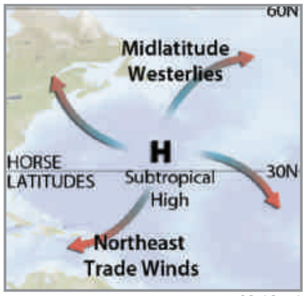
5. The top part of the graph below shows how the combination of a northward-directed pressure-gradient force and eastward-directed Coriolis effect results in the westerlies in the Northern Hemisphere. The Coriolis effect strengthens with increasing latitude, turning winds even more to the east as they move north.



6. In the Southern Hemisphere, air is driven south by high pressure in the subtropics. As this air flows south, it is deflected to the east by the Coriolis effect. The result is again west-to-east flow in the middle latitudes, forming a Southern Hemisphere belt of westerlies. Note that in both the Northern and Southern Hemispheres, the Coriolis effect is deflecting flows in the mid-latitudes toward the east, in the direction the Earth is rotating.

7. The Southern Hemisphere has a belt of low pressure (the subpolar lows) caused by rising air in the polar cell. Air flows toward these lows and away from the subtropical highs, deflecting to the east and becoming westerlies. These westerlies are especially strong (there are no wind-blocking continents) and so are called the *roaring forties* (between 40° S and 50° S latitude).

Circulation Around Highs and Lows in the Northern Hemisphere



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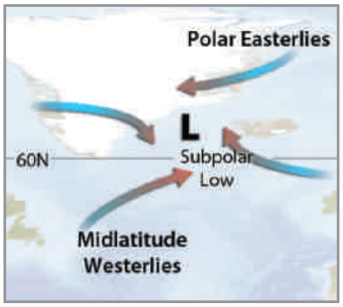
1. In the Northern Hemisphere, high pressure commonly occurs in the subtropics, along the horse latitudes. Winds around the highs are deflected in a clockwise direction by the Coriolis effect. Winds north of the high reinforce the westerlies, whereas winds to the south reinforce the easterly trade winds. As winds spin around the high, they push cold air equatorward and warm air poleward.



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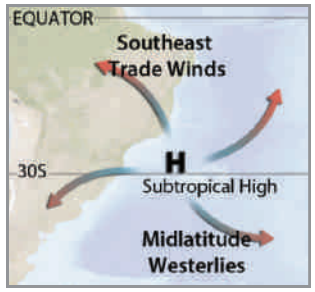
2. Circulation around lows, including subpolar lows, is counterclockwise in the Northern Hemisphere. The subpolar lows reside between polar easterlies to the north and westerlies to the south (in the mid-latitudes). The rising air and shearing between opposite-directed winds causes windy, stormy conditions.

Circulation Around Highs and Lows in the Southern Hemisphere



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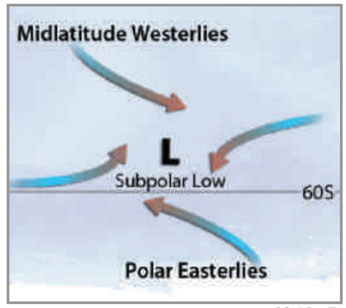
3. In the Southern Hemisphere, high pressure around the subtropics is accompanied by counterclockwise circulation. The highs are situated between southeast trade winds to the north and westerlies in the mid-latitudes to the south. As in the Northern Hemisphere, circulation around pressure systems redistributes warm and cold air and moisture.



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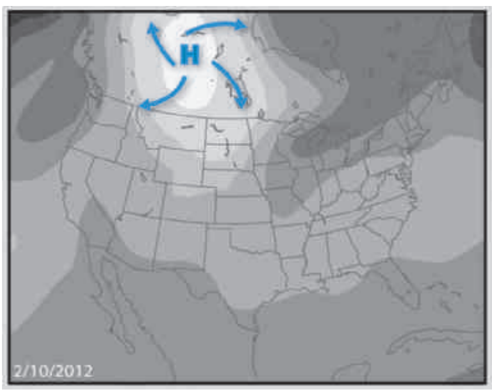
4. Lows in the Southern Hemisphere, such as the subpolar lows, have clockwise circulation around the low. The lows lie between the westerlies and polar easterlies, and this latitudinal belt is extremely windy and stormy. At this latitude there are few large landmasses to disrupt the winds.

Migration of Pressure Areas in the Mid-Latitudes



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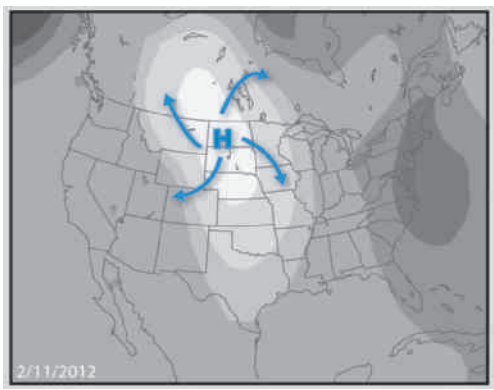

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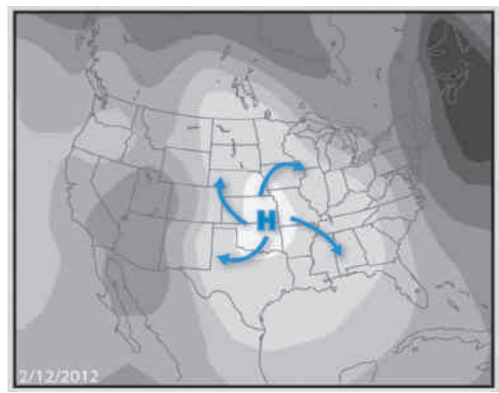

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5. Embedded within the mid-latitude westerlies are traveling, spinning circulations of high and low pressure, much like a swirling flow that is embedded within the overall current in a stream. The four figures here show the movement of a high-pressure area (an *anticyclone*) guided by the mid-latitude westerlies. Anticyclones generally move equatorward as they migrate eastward, as shown in this series of daily images. Traveling low-pressure systems called *cyclones*, not shown here, tend to move poleward as they travel from west to east across the mid-latitudes; they are associated with stormy weather. As either type of pressure migrates through an area, it causes the wind direction to change relatively suddenly. As a result, wind and other weather patterns change more quickly in the mid-latitudes than in any other part of the Earth.

03.12.a11

6. Note how the winds change in any area across which the pressure area migrates. In the case shown here, an area has northwesterly winds as the high pressure approaches from the northwest, followed by southeast winds once the high has passed to the east.

Before You Leave This Page Be Able To

- ✓ Sketch, label, and describe the general circulation in the mid-latitudes, in both the Northern and Southern Hemispheres, and explain the processes that cause air in the mid-latitudes to circulate generally from west to east.
- ✓ Sketch, label, and explain the circulation around areas of high and low pressure, and how they relate to the prevailing winds.
- ✓ Summarize the overall movement of mid-latitude cyclones and anticyclones.

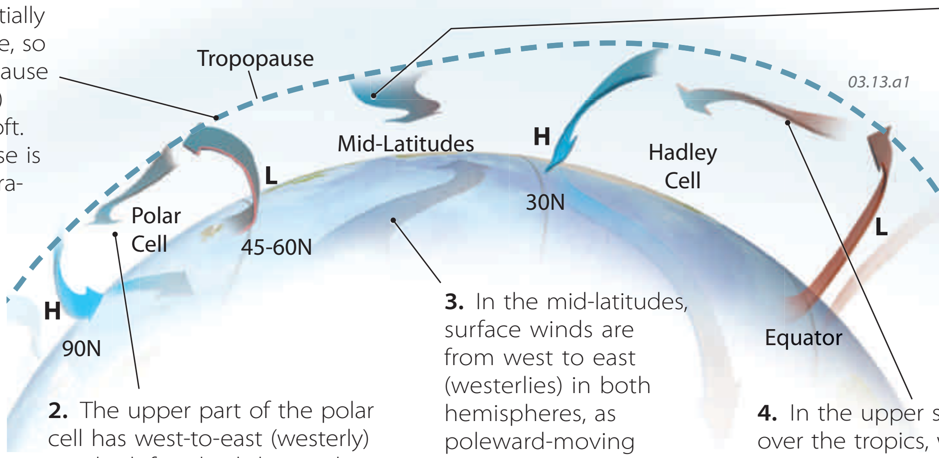
3.13 How Does Air Circulate Aloft over the Mid-Latitudes?

SURFACE WINDS IN THE MID-LATITUDES are generally from west to east in both hemispheres, but the pattern of air movement is less well developed higher in the troposphere. The main features are two currents of fast-moving air — jet streams — that encircle the globe near the boundaries of the mid-latitudes. What factors determine the direction and speed of airflow aloft in the mid-latitudes, such as in the jet streams?

A What General Circulation Occurs Aloft over the Westerlies?

The main direction of surface air in the mid-latitudes is as curving arcs that move poleward away from the subtropics and then bend increasingly to the east, becoming westerlies. What happens aloft? The figure below shows the setting of upper-level airflows in the mid-latitudes, between the polar cell and the Hadley cell.

1. Circulation of air is essentially restricted to the troposphere, so the geometry of the tropopause (the top of the troposphere) influences the flow of air aloft. The height of the tropopause is largely controlled by temperatures in the underlying troposphere and whether the underlying air rises or sinks. As a result, the tropopause is shallower (8 km or less) over the poles, where cold, dense air sinks, than over the equator (16 km or more), where air is warmer and rises; it increases in height from the poles across the mid-latitudes.



2. The upper part of the polar cell has west-to-east (westerly) winds aloft in both hemispheres, in response to the strong Coriolis effect at high latitudes. Surface winds are easterlies.

3. In the mid-latitudes, surface winds are from west to east (westerlies) in both hemispheres, as poleward-moving winds are turned east by the Coriolis effect.

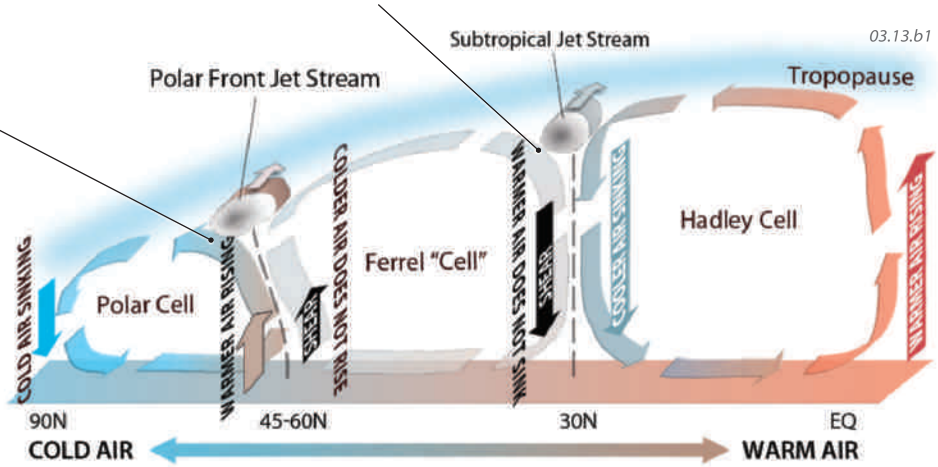
4. In the upper segment of the Hadley cell, over the tropics, winds aloft move southwest to northeast in the Northern Hemisphere, but northwest to southeast in the Southern Hemisphere; upper-level flows in both areas are therefore westerlies.

5. If surface winds in the mid-latitudes and the winds on both sides are moving overall from west to east (in both hemispheres), it is logical that the winds aloft over mid-latitudes will also be westerly. Friction is less aloft than at the surface, so the upper-level westerlies over the mid-latitudes are stronger than westerlies at the surface.

B Is There a Circulation Cell in the Mid-latitudes?

1. If there were a cell of circulating air in the mid-latitudes, as there is in the tropical and polar latitudes, then the sinking from the poleward edge of the Hadley cell would cause shear that would also induce sinking at the equatorward edge of the mid-latitudes.

2. Likewise, the rising motion at the equatorward edge of the polar cell (the subpolar lows) would induce rising next to the poleward edge of the mid-latitudes. This rising motion, coupled with the sinking next to the Hadley cell, would logically set up upper-level circulation over the mid-latitudes, with air moving from the pole toward the tropics. This hypothetical mid-latitude circulation system is known as the *Ferrel cell*.



3. Descending air near the subtropical highs flows poleward along the surface and is turned toward the east by the Coriolis effect, contributing to the mid-latitude westerlies. Aloft, some rising air at the subpolar lows moves equatorward.

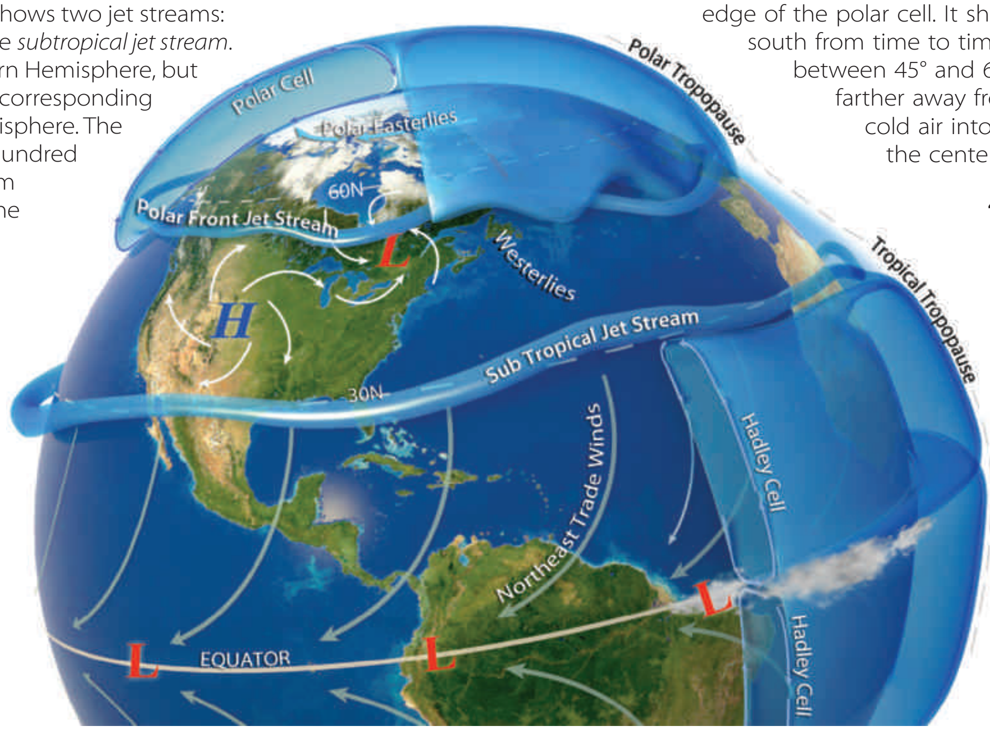
4. However, other factors cause the Ferrel cell to be developed very weakly or not at all. Thermal properties, which result in differences in air density, also dictate whether air will rise. Air on the subtropical side of the Ferrel cell (near 30° latitude) is relatively warm, and so it should be rising, not sinking. Air on the polar side of the cell is colder, and so it should be sinking, not rising. In other words, the thermal effects of the Ferrel cell's warmer air rising and cooler air sinking somewhat offset the dynamic effect of the shear from the adjacent Hadley and polar cells. The result is the near absence of a circulation cell in the mid-latitudes.

C What Are Jet Streams and How Do They Form?

Fast-moving, relatively narrow currents of wind, called *jet streams*, flow aloft along the boundaries of the mid-latitude air currents. One jet stream is located along the edge of the polar cell and another is along the edge of the tropical Hadley cell. How do such jet streams form and what controls their locations?

1. Jet streams are strong air currents that are long and relatively narrow, resembling a ribbon or tube wrapping around the planet. This figure shows two jet streams: the *polar front jet stream* and the *subtropical jet stream*. They are shown for the Northern Hemisphere, but equivalents are also present in corresponding positions in the Southern Hemisphere. The jet streams are typically a few hundred kilometers wide and about 5 km thick, and are located high in the troposphere, near the tropopause. They generally follow paths that curve or meander and can locally split into separate strands that eventually rejoin. The four jet streams all blow from west to east as a result of Earth's rotation.

2. The subtropical jet stream circles around the globe at about 30° latitude (in both hemispheres), near the boundary between the Hadley cell and westerlies aloft in the mid-latitudes.



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3. In both the north and south hemispheres, the polar front jet stream encircles the globe near the edge of the polar cell. It shifts position north and south from time to time, but typically resides between 45° and 60° latitude. As it shifts farther away from the pole, it brings cold air into the mid-latitudes, like the center of North America.

4. In addition to influencing weather, jet streams affect air travel in good and bad ways. A plane flying in the same direction as the jet stream (to the east) moves faster than normal, but a plane flying against the jet stream (west) is slowed. Jet streams also cause clear-sky turbulence on flights.

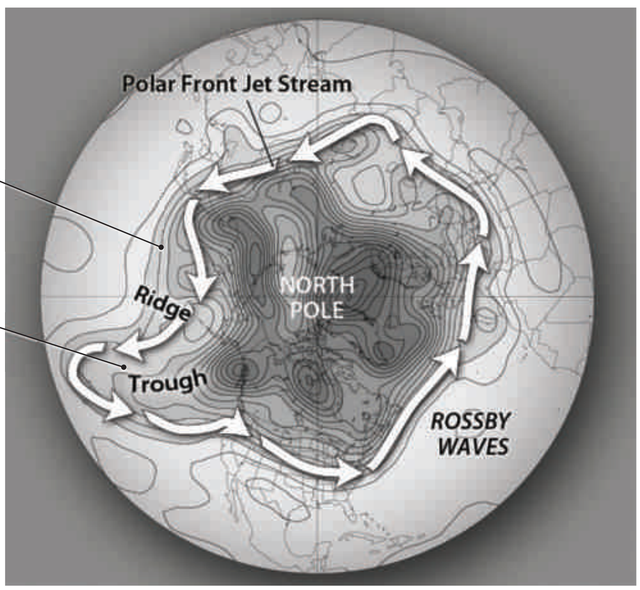
D What Are Rossby Waves and How Do They Relate to Jet Streams?

1. Jet streams do not track around the planet along perfectly circular routes, but instead typically follow more irregular curved paths, like along the thick white line in the polar projection below. These meandering paths, when viewed in three dimensions, resemble curving waves, and are called *Rossby waves* after the scientist who discovered them. The lines on this map, which is viewed directly down on the North Pole, are isohypses with dark colors showing local areas of low heights (low pressure). Notice that these are concentrated in the subpolar areas.

2. Where the polar jet stream curves toward the pole, this part of the jet stream is called a *ridge*. Ridges bend poleward.

3. Where the polar jet stream curves away from the pole, we call that type of curve a *trough*. Troughs bend equatorward.

4. The size and position of ridges and troughs is not constant, but changes over days, weeks, and months. Troughs can get "deeper" or "shallower," while ridges get "stronger" or "weaker."



03.13.d1

5. Bends in the polar jet stream (Rossby waves) have a great influence on weather in nearby parts of the mid-latitudes. When a trough becomes more accentuated and shifts farther away from the pole (i.e., it deepens), it allows cold Arctic air to extend farther away from the pole. Also, as discussed in the weather chapter, Rossby waves influence surface high and low pressures near the polar jet and help strengthen, weaken, and guide mid-latitude cyclones as they migrate across the surface. Accordingly, we return to Rossby waves later.

Before You Leave This Page Be Able To

- ✓ Describe the flow of air aloft over the mid-latitudes.
- ✓ Sketch, label, and explain the two types of jet streams.
- ✓ Sketch and explain Rossby waves, including a trough and ridge.

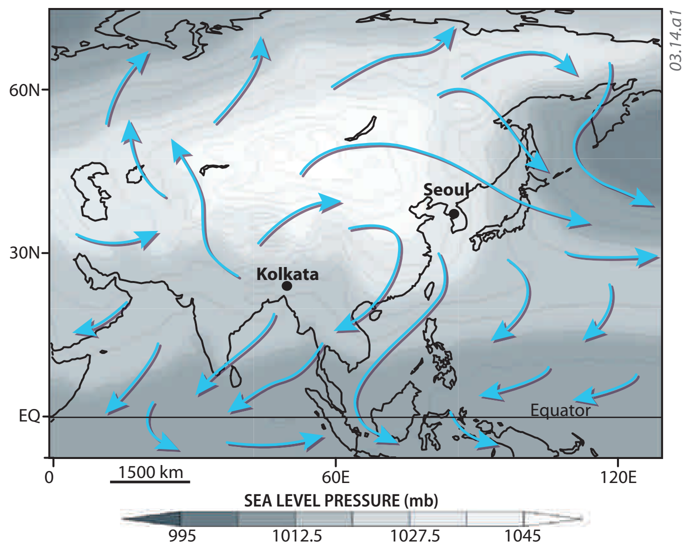
3.14 What Causes Monsoons?

A COMMON MISCONCEPTION is that the word "monsoon" refers to a type of rainfall, but the word actually refers to winds that reverse directions depending on the season. One of these seasonal wind directions typically brings dry conditions and the other brings wet conditions. Monsoons impact a majority of the world's population.

A What Are the Features of the Asian Monsoon?

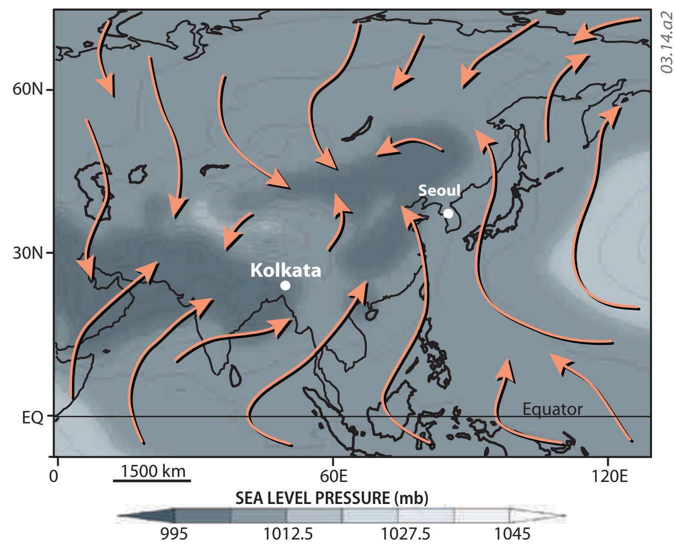
One way to characterize a monsoon is to compare maps showing wind directions for different times of the year. Such maps can then be compared to rainfall records to determine which seasonal wind directions bring dry conditions and which ones bring wet conditions. The maps below show climatological wind conditions for the years 1981 through 2010 for two months — January and July. Arrows show wind directions, and shading represents pressure at sea level, with light gray being high and dark gray being low. Examine the patterns of circulation for each month and then compare the patterns between the months.

03.14.a1



January—This map shows typical wind conditions for Asia during January. In the center of the map, winds define a region where flow is clockwise and outward, centered on the light-colored area of high pressure. This high-pressure area (anticyclone) forms from cold, sinking air over Siberia. This circulation brings very dry air (from the cold interior of the continent) from the north over southern Asia and from the northwest across eastern Asia. We would predict from these wind patterns that little precipitation would occur in much of Asia at this time.

03.14.a2

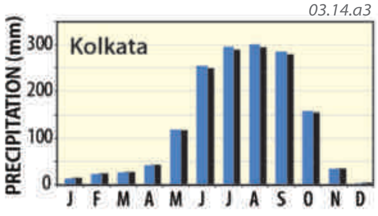


July—This map shows that wind conditions for the same region during July are totally different than they are for January. Circulation that marked the high pressure is gone, replaced by an area of inward and counterclockwise flow over Tibet (north of Kolkata). In the Northern Hemisphere, this pattern of circulation is diagnostic of a low-pressure area, which in this case is caused by warm, rising air that accompanies warming of the Asian landmass. This circulation brings very humid air from the southwest over southern and southeastern Asia. How do you think this circulation affects rainfall?

Seasonal Variation in Precipitation

Observe these graphs showing average monthly precipitation amounts for two very different parts of Asia: Kolkata, one of the largest metropolitan areas of India, and Seoul, the capital of South Korea. For both cities, notice prominent precipitation peaks that occur during the summer — the wet season. The increase in precipitation during the wet season results from the flow of moist air from oceans onto land, toward the *Tibetan Low*. The dry season, during the winter months, reflects the flow of dry air from the land, flowing outward from the *Siberian High*.

03.14.a3



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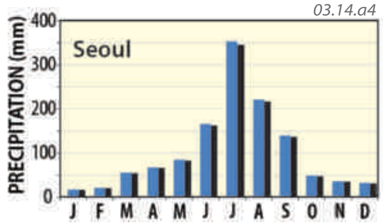


Effect of the Monsoon on Vegetation

These satellite images show increased vegetation due to monsoon-related rains along the western coast of India. The left image is during the dry season, when wind patterns bring in dry air. The right image is from the end of the monsoon. Note the increase in plant cover (green areas) during the monsoon-caused rainy season.

03.14.a5 India

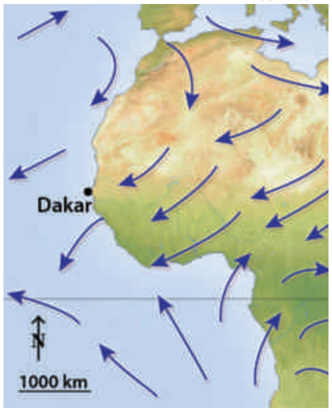
03.14.a6 India

B What Other Regions Experience Monsoon Circulations?

West Africa

January—In January, near-surface winds in West Africa largely flow from the northeast bringing in dry air from inland areas, including the Sahara Desert, and carrying it southwest to coastal areas and farther offshore. Such *offshore flows* generally result in dry weather.

03.14.b1



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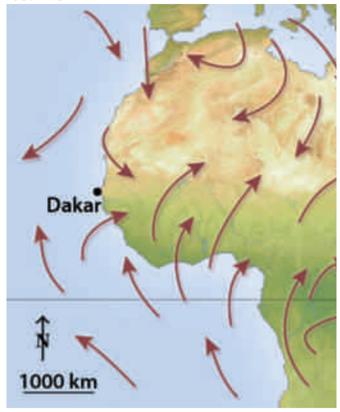
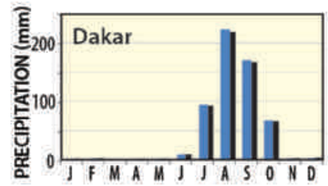


July—A shift in wind direction in July brings moist ocean air from several directions onto the very hot land where air has risen This change in wind direction causes enormous differences in precipitation, as shown by the graph below for Dakar, Senegal. Along with the increase in precipitation comes an increase in the amount of vegetation. In Dakar and much of the region, precipitation is nearly nonexistent in January and adjacent months.

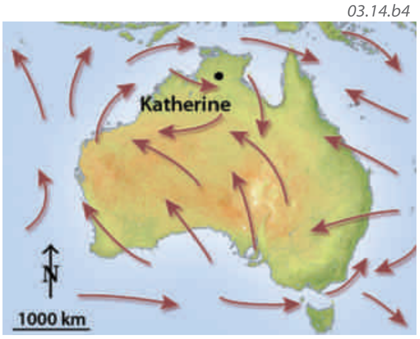


03.14.b3

Northern Australia

January—In January (the southern summer), winds over northern Australia bring moist air from the ocean onto the heated land surface.

03.14.b4



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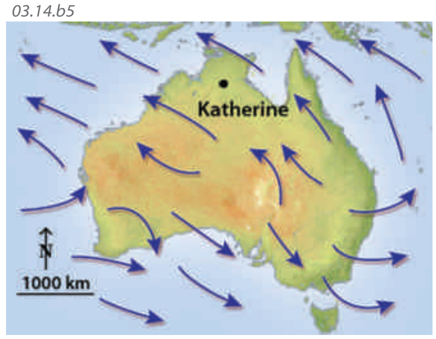
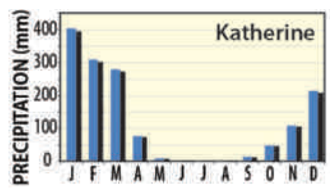


July—The wind shifts by July (winter) as the land surface cools, creating higher pressure over the land. This causes a large drop in precipitation, as shown by the graph below for Katherine, Australia. The monsoon flow in January results in plentiful rain.

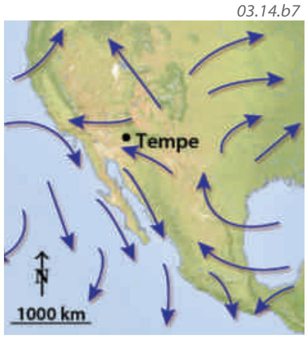


03.14.b6

Southwestern U.S.

January—Southwestern North America, most of which is desert, has a less dramatic, but still important monsoon effect. In the winter months, winds blow from various directions, and winter precipitation in this region is from brief incursions of cold, wet air (i.e., cold fronts) from the northwest.

03.14.b7



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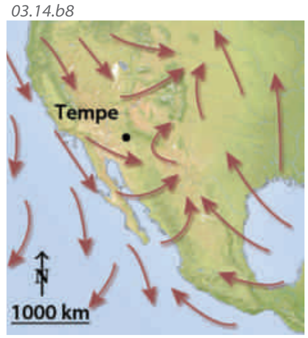
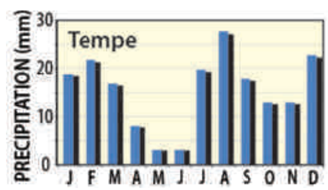


July—During the late summer months, heating of the land surface and the resulting low pressure causes a shift in winds. Winds from the south bring moist air northward from the Gulf of Mexico and Gulf of California, and summer thunderstorms from when this air interacts with the heated land. These summer thunderstorms cause precipitation to peak in August, as shown by the graph below for Tempe, Arizona. First, note the different scale needed to show the relatively small amounts of precipitation. Also note that nearly as much precipitation falls in the winter from the cold fronts.



03.14.b9

The Effect of Monsoons on Cultures

Monsoons greatly influence the lives of people living in regions with seasonal shifts in wind. The main effects of a monsoon are seasonal variations in precipitation, which in turn affect water supplies, amount of vegetation, and overall livability for some normally dry landscapes. Many cultures plan their activities around these seasonal changes, conserving water during the dry season and taking advantage of the plentiful water during the wet season.

The monsoon pervades the psyches of people in southern and southeastern Asia, especially the region from India to Vietnam, in ways not fathomable to most North Americans or Europeans. The influence on agriculture, including the cultivation of rice, and on flooding and other natural hazards is obvious, but the monsoon also appears in literature, art, music, architecture, and nearly every other aspect of culture. Ceremonies commonly mark the anticipated start of the monsoon. In years when the monsoon rains arrive later than usual, people become very concerned that harvests will suffer. The date of the onset of the monsoon rains varies by location, but generally proceeds from south to north with the onset in April and May.

Before You Leave This Page Be Able To

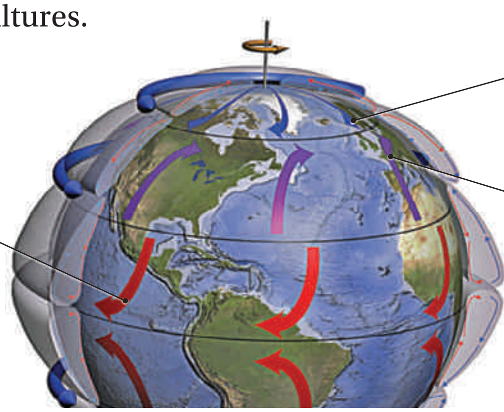
- ✓ Explain what causes a monsoon, using examples from Asia, West Africa, northern Australia, and southwestern North America.
- ✓ Describe some of the effects of shifting monsoonal winds.

CONNECTIONS

3.15 How Have Global Pressures and Winds Affected History in the North Atlantic?

INTERCONTINENTAL TRAVEL AND TRADE have relied upon moving currents in the air and oceans. Before the 20th century, when transoceanic travel and shipping relied on wind power, global winds, such as the trade winds and westerlies, dictated which directions of travel were possible at different latitudes. The directions of global winds therefore greatly influenced the exploration and colonization of the Americas, and traces of that influence can be detected in past and present cultures.

This small globe (►) shows the main belt of global winds, controlled by the pressure-gradient force and Coriolis effect. Can you locate and name the main wind belts? In the Northern Hemisphere, trade winds (shown in red) blow from northeast to southwest, allowing wind-powered sailing ships to travel from western Africa to Central America and the northern part of South America.



03.15.a2

The polar easterlies (shown in blue) likewise allowed westward travel, but under cold and stormy conditions.

In contrast, westerlies (shown in purple) allowed a return trip from North America to Europe, but only in the mid-latitudes. Ships commonly had to travel north or south along coasts to catch a prevailing wind going in the direction of intended travel across the Atlantic Ocean.

03.15.a3 Cotton plantation along the Mississippi River

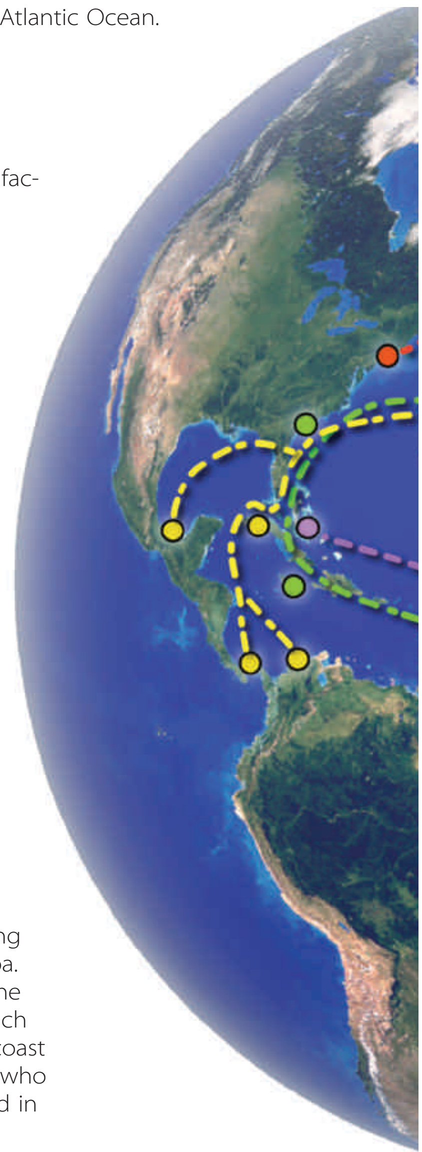
◄ Plantations in the southeastern U.S. depended upon African slave labor to cultivate and harvest cotton, tobacco, and tropical agricultural products. In contrast, the economy of the northeastern U.S. was based more upon manufacturing and the refining of products grown on the southern plantations, with the final refined product being exported to western Europe. The traditional cultural divide between the northern states and southern states is the Mason-Dixon line (near 40° N), which corresponds roughly to the global climatological divide between the zones of excess climatic energy to the south and an energy deficit to the north. The excess and deficit energy settings controlled which crops could be grown in the two regions and allowed different kinds of activities by impacting the climate. This climate-energy boundary contributed to the political and social attitudes that existed then and today.

03.15.a4 Sugar plantation

Slaves and various provisions were brought from Africa on ships utilizing the trade winds on either side of the equator, winds that provided a direct conduit of trade from western Africa to equatorial parts of the Americas. Most slaves were put to work on labor-intensive tasks, such as agriculture, in and around the tropical regions of the Caribbean (◄). Their descendants still exert a great influence over the distinct culture of the islands and coastal areas in the region.

03.15.a5 Sir Francis Drake

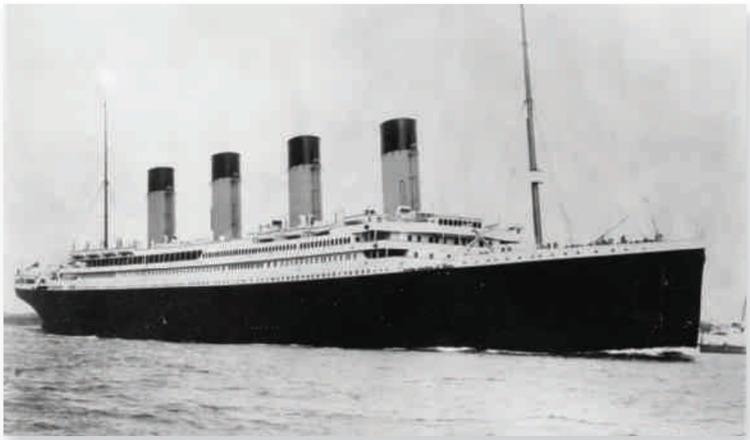
After Portugal and Spain agreed to divide the "new" world into two separate spheres of influence, the Spanish encountered difficulty in transporting products and plunder from the Pacific empire across Portuguese territories, especially Brazil. Spanish goods were brought to Caribbean ports or were transported across the isthmus of Central America, before being stockpiled temporarily in Spanish ports in the tropics, including Havana, Cuba. Treasure-bearing sailing ships departing tropical ports had to sail north up the coast of Anglo-America (the yellow paths on the large globe) in order to reach the mid-latitude westerlies, which then carried the ships east to Spain. This coast provided an ideal safe haven for English privateers, like Sir Francis Drake (◄), who captured many ships and their content, enriching the privateers and England in the process, and laying the financial foundation for the British Empire.



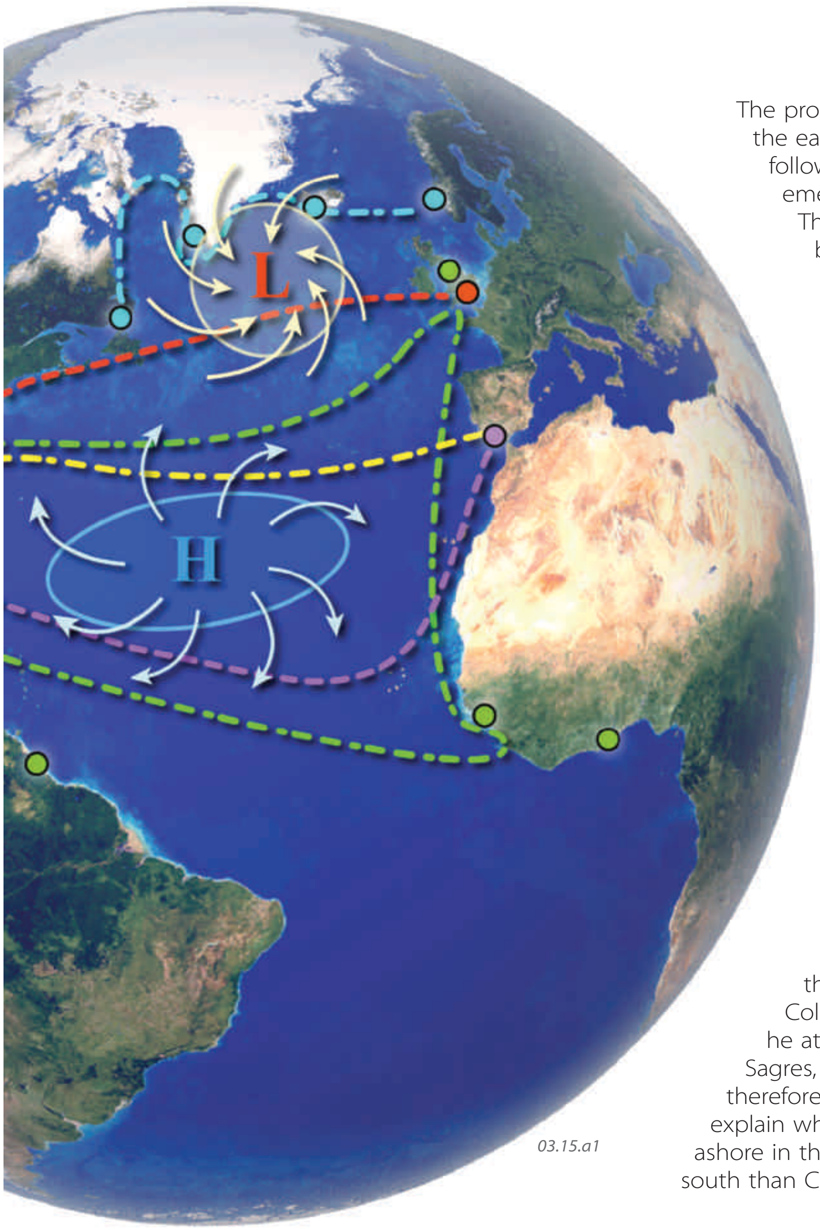
03.15.a6 Remains of Viking settlement, Iceland

◄ The Viking explorer Leif Erickson probably visited North America about 500 years before Christopher Columbus. Moving westward from Scandinavia, the Vikings progressively colonized Iceland and Greenland before journeying across the Davis Straits to Baffin Island and the coast of Labrador (the blue path on the globe). The remains of a Viking settlement have been found on the most northerly tip of Newfoundland at L'Anse Aux Meadows. Viking ships would have employed the polar easterlies and associated ocean currents to aid their westward migration. Ironically, a shift to a much colder climate in the late 15th century caused the extinction of the settlements in Greenland at exactly the same time as Columbus was embarking on his explorations.

03.15.a7 Titanic



▲ When the steam-powered Titanic left Southampton, England (51° N), for New York City (41° N) in April 1912, global winds and currents were no longer such a strong determinant of oceanic travel routes. The planned northerly route (red path on the globe), however, crosses a treacherous part of the North Atlantic Ocean—the region with stormy weather near the subpolar lows. The Titanic sank at 42° N off the east coast of Canada, striking an iceberg brought south by global winds and ocean currents.



03.15.a1

The prosperity of many trading ports in western Europe and the Americas (▼) during the early 19th century was based on various types of interconnected trade that followed a triangular path (green path on the globe). Manufactured goods from the emerging European industrial economies were loaded for trade with West Africa. There, African slaves were taken on board and carried west by the trade winds to the Americas. Once in the Americas, the slaves were traded for the products of the tropical plantation system. Using the westerlies, the raw goods were returned to western Europe for consumption or industry. The triangular path was designed to maximize favorable winds and to avoid the subtropical high pressures and calm winds of the horse latitudes.

03.15.a8 New Orleans, LA

Departing from Cadiz, Spain (36° N), Christopher Columbus wanted to sail west, but first had to sail south down the northwestern coast of Africa to avoid the westerlies and instead pick up the northeast trade winds (the purple path on the globe). Portuguese navigators had known this strategy for many years, and Columbus probably learned of it when he attended the school of navigation in Sagres, Portugal. Global wind patterns therefore controlled Columbus's path and explain why in all likelihood, he first stepped ashore in the Bahamas (24° N), much farther south than Cadiz, where he started.

Before You Leave This Page Be Able To

✓ Sketch and describe the main features of atmospheric circulation in the northern Atlantic Ocean and how they influenced early travel.

INVESTIGATION

3.16 What Occurs During Seasonal Circulation Shifts?

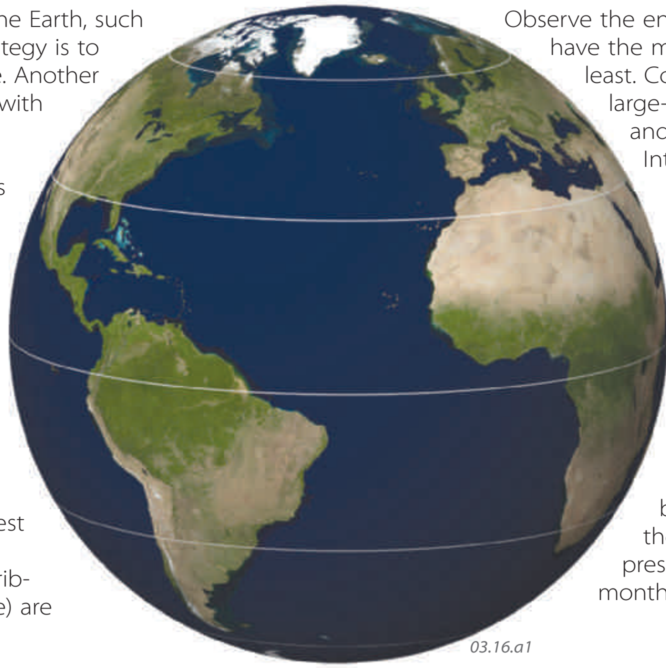
GLOBAL ATMOSPHERIC CIRCULATION responds directly to insolation. As the Sun's direct rays migrate seasonally, belts of winds, such as the westerlies, migrate too. In this investigation, you will examine the general circulation of the atmosphere, as expressed by data on air pressure, wind velocity, and cloud cover for two months with very different seasons — January and July.

Goals of This Exercise:

- Identify major patterns in air pressure, wind velocity, and cloud cover for each season.
- From these data, identify the major features of the global atmospheric circulation in each season.
- Assess and explain the degree of seasonal movement of these circulation features.

When examining large-scale patterns of the Earth, such as global circulation patterns, a useful strategy is to focus on one part of the system at a time. Another often-recommended strategy is to begin with relatively simple parts of a system before moving to more complex ones. For this investigation, you will infer global patterns of air circulation by focusing on the Atlantic Ocean and adjacent lands (▶).

This globe is centered on the central Atlantic, and its top is slightly tilted toward you to better show the Northern Hemisphere. As a result of this tilt, Antarctica is barely visible at the bottom of the globe. The colors on land, derived from satellite data, depict rocks and sand in tan and brown. Vegetation is in various shades of green, with the darkest green indicating the thickest vegetation (usually forests). Shallow waters in the Caribbean region (on the left side of the globe) are light blue.



03.16.a1

Observe the entire scene, noting which areas on land have the most vegetation and which ones have the least. Compare these vegetation patterns with large-scale patterns of atmospheric circulation and air pressure, like subtropical highs and the Intertropical Convergence Zone ITCZ).

Consider what directions of prevailing winds would occur in different belts of latitude. For example, where in this globe are the two belts of trade winds (one north and one south of the equator)? How about the mid-latitude belts of westerlies in each hemisphere? Consider how these winds might blow moisture-rich air from the ocean onto land. After you have thought about these aspects, read the procedures below and examine the globes and text on the next page, which highlight average air pressure, wind velocity, and cloud cover for two months — January and July.

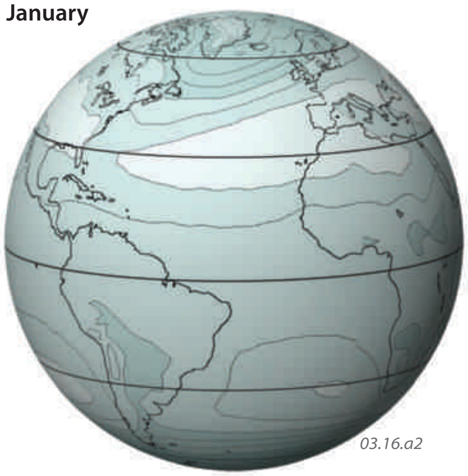
Procedures

Complete the following steps on a worksheet provided by your instructor or as an online activity.

1. Study the two globes showing air pressure (on the next page), and note areas with high and low pressure. Locate the Icelandic Low and Bermuda-Azores High, and determine for which season each is strongest or if there is not much difference between the seasons. Then, locate a belt of low pressure near the equator and the adjacent belts of subtropical highs on either side. Mark and label the approximate locations of these features on the globe on the worksheet.
2. Next, examine the two globes that show wind velocity. In the appropriate place on the worksheet, draw a few arrows to represent the main wind patterns for different regions in each month. Label the two belts of westerlies and the two belts of trade winds. If the horse latitudes are visible for any hemisphere and season, label them as well. Mark any somewhat circular patterns of regional winds and indicate what pressure feature is associated with each.
3. Examine the two globes that show the average cloud cover for each month. From these patterns, label areas that you interpret to have high rainfall in the tropics due to proximity to the ITCZ or low rainfall due to position in a subtropical high. Examine how the cloud patterns correspond to the amount of vegetation, pressure, and winds.
4. Sketch and explain how the different features of circulation and air pressure change between the two months. Answer all the questions on the worksheet or online. OPTIONAL EXERCISE: Your instructor may have you write a short report (accompanied by a sketch) summarizing your conclusions and predicting how seasonal shifts would affect people.

Air Pressure

January



03.16.a2

July

03.16.a3

These two globes show average air pressure over the Atlantic and adjacent land areas during the months of January and July. Lighter gray indicates relatively high pressures, whereas darker gray indicates low pressures. Intermediate grays indicate intermediate pressures. The lines encircling the globe are the equator and 30° and 60° (N and S) latitudes.

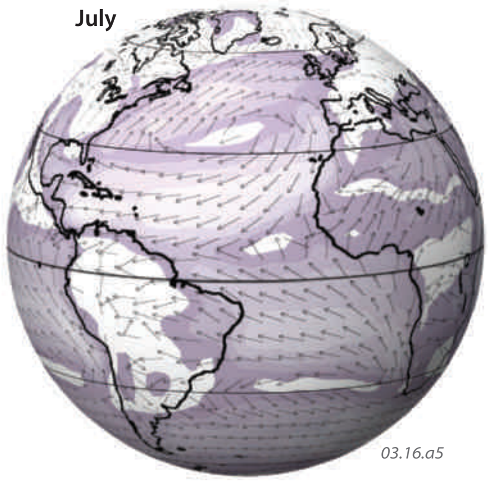
Observe the main patterns on these two globes, noting the positions of high pressure and low pressure and how the positions, shapes, and strengths change between the two seasons. Then, complete the steps described in the procedures section.

Wind Velocity

January

03.16.a4

July



03.16.a5

These globes show average wind velocities for January and July. The arrows show the directions, while the shading represents the speed, with darker being faster. In this exercise, the directions are more important than the speeds, but both tell part of the story.

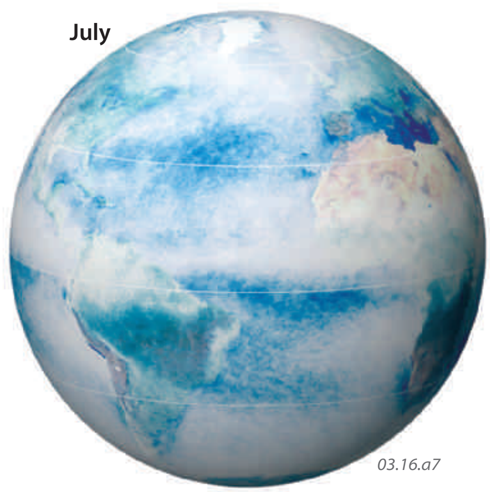
Observe the large-scale patterns, identifying those patterns that are related to global circulation (i.e., westerlies) versus those that are related to more regional features, such as the Bermuda-Azores High and the Icelandic Low. Note also the position of where winds converge along the equator and how this position changes between the two months.

Cloud Cover

January

03.16.a6

July



03.16.a7

The clouds that form, move above Earth's surface, and disappear can be detected and tracked with satellites, shown here for January and July 2012. On these globes, light colors that obscure the land and ocean indicate more abundant clouds (and often precipitation), whereas the land shows through in areas that average fewer clouds.

Observe the large-scale patterns, noting which areas are cloudiest and which ones generally have clear skies. Relate these patterns of clouds to the following: amount of vegetation on the land, air pressure for that month, and average wind directions. Answer all questions on the worksheet or online.