17.1 Atmosphere Characteristics

Reading Focus

Key Concepts

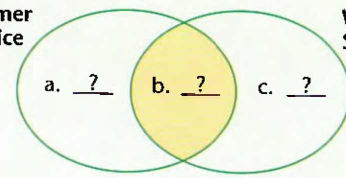
- How does weather differ from climate?
- Why do seasonal changes occur?

Vocabulary

- ozone
- troposphere
- stratosphere
- mesosphere
- thermosphere
- summer solstice
- winter solstice
- autumnal equinox
- spring equinox

Reading Strategy

Comparing and Contrasting Copy the Venn diagram below. As you read, complete the diagram by comparing and contrasting summer and winter solstices.



Earth's atmosphere is unique. No other planet in our solar system has an atmosphere with the exact mixture of gases or the moisture conditions and heat needed to sustain life as we know it. The gases that make up Earth's atmosphere and the controls to which they are subject are vital to our existence. In this chapter, you will begin to examine the ocean of air in which we live.

The state of the atmosphere at a given time and place is known as weather. The combination of Earth's motions and energy from the sun produce a variety of weather. As shown in Figure 1, weather strongly influences our everyday activities. **Weather is constantly changing, and it refers to the state of the atmosphere at any given time and place. Climate, however, is based on observations of weather that have been collected over many years. Climate helps describe a place or region.** Climate often is defined simply as "average weather," but this is not a complete description. For example, farmers need to know not only the average rainfall during a growing season, but they also need to know the frequency of extremely wet and extremely dry years. The most important measurable properties of weather and climate are air temperature, humidity, type and amount of precipitation, air pressure, and the speed and direction of the wind.

Figure 1 Buffalo, New York, was under a state of emergency in late December 2001 after receiving almost 2 meters of snow.

Reading Checkpoint *How does weather differ from climate?*

Composition of the Atmosphere

The composition of the atmosphere has changed dramatically over Earth's nearly 4.6 billion year history. The atmosphere is thought to have started as gases that were emitted during volcanic eruptions. Evidence indicates that oxygen did not start to accumulate in the atmosphere until about 2.5 billion years ago. The atmosphere continues to exchange material with the oceans and life on Earth's surface.

Major Components Sometimes the term *air* is used as if it were a specific gas, which it is not. Air is a mixture of different gases and particles, each with its own physical properties. The composition of air varies from time to time and from place to place. However, if the water vapor, dust, and other variable components were removed from the atmosphere, its makeup would be very stable worldwide up to an altitude of about 80 kilometers.

Look at Figure 2. Two gases—nitrogen and oxygen—make up 99 percent of the volume of clean, dry air. Although these gases are the most common components of air, they don't affect the weather much. The remaining 1 percent of dry air is mostly the inert gas argon (0.93 percent) plus tiny quantities of a number of other gases. Carbon dioxide is present in only small amounts (approximately 0.039 percent), but it is an important component of air. Carbon dioxide is an active absorber of energy given off by Earth. Therefore, it plays a significant role in heating the atmosphere.

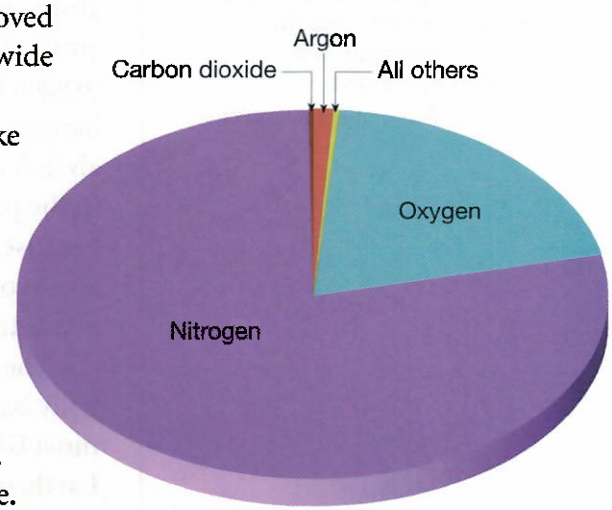


Figure 2 Volume of Clean, Dry Air Nitrogen and oxygen dominate the volume of gases composing dry air.

Variable Components Important materials that vary in the air from time to time and place to place include water vapor, dust particles, and ozone. These components also can have significant effects on weather and climate.

The amount of water vapor varies from almost none to about 4 percent by volume. Why is such a small quantity so significant? **Water vapor is the source of all clouds and precipitation. Like carbon dioxide, water vapor absorbs heat given off by Earth. It also absorbs some solar energy.**

Movements of the atmosphere allow a large quantity of solid and liquid particles to be suspended within it. Although visible dust sometimes clouds the sky, these relatively large particles are too heavy to stay in the air for very long. Still, many particles are microscopic and remain suspended for longer periods of time. These particles include sea salts from breaking waves, fine soil blown into the air, smoke and soot from fires, pollen and microorganisms lifted by the wind, and ash and dust from volcanic eruptions.

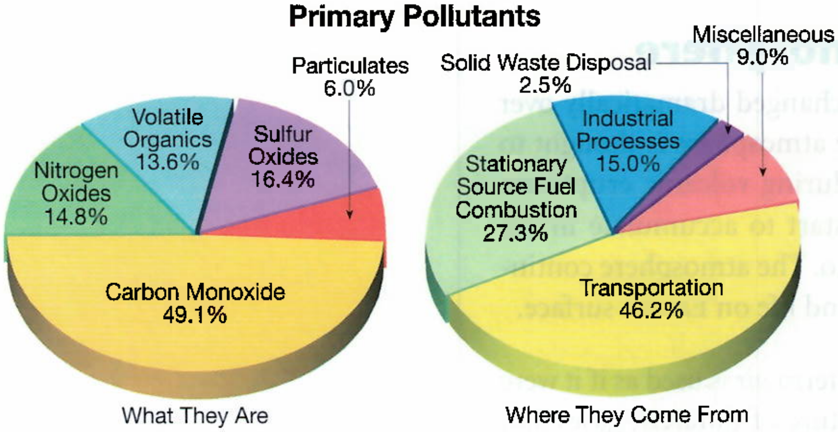


Figure 3 Primary Pollutants These circle graphs show major primary pollutants and their sources. Percentages are calculated by weight.

Source: U.S. Environmental Protection Agency.

Another important variable component of the atmosphere is ozone. **Ozone** is a form of oxygen that combines three oxygen atoms into each molecule (O_3). Ozone is not the same as the oxygen we breathe, which has two atoms per molecule (O_2). There is very little ozone in the atmosphere, and it is not distributed evenly. It is concentrated in a layer located between 10 and 50 kilometers above Earth's surface.

In this altitude range, oxygen molecules (O_2) are split into single atoms of oxygen (O) when they absorb ultraviolet (UV) radiation emitted by the sun. Ozone is then produced when a single atom of oxygen (O) and a molecule of oxygen (O_2) collide. This collision must happen in the presence of a third, neutral molecule that acts as a catalyst. A catalyst allows a reaction to take place without being consumed in the process. Ozone is concentrated 10 to 50 kilometers above Earth because the UV radiation from the sun is sufficient to produce single atoms of oxygen. In addition, there are enough gas molecules to bring about the required collisions.

The ozone layer is crucial to life on Earth. Ozone absorbs potentially harmful UV radiation from the Sun. **If ozone did not filter most UV radiation and all of the sun's UV rays reached the surface of Earth, our planet would be uninhabitable for many living organisms.**

Human Influence Air pollutants are airborne particles and gases that occur in concentrations large enough to endanger the health of organisms. Primary pollutants, shown in Figure 3, are emitted directly from identifiable sources. Emissions from transportation vehicles account for nearly half the primary pollutants by weight.

Secondary pollutants are not emitted directly into air. They form in the atmosphere when reactions take place among primary pollutants and other substances. For example, after the primary pollutant sulfur dioxide enters the atmosphere, it combines with oxygen to produce sulfur trioxide. Then the sulfur trioxide combines with water to create sulfuric acid, an irritating and corrosive substance.

Reactions triggered by strong sunlight are called photochemical reactions. For instance, when nitrogen oxides absorb solar radiation, a chain of complex reactions begins. If certain volatile organic compounds are present, secondary products form that are reactive, irritating, and toxic. This noxious mixture of gases and particles is called photochemical smog.

Reading Checkpoint *What are secondary pollutants?*

Height and Structure of the Atmosphere

Where does the atmosphere end and outer space begin? There is no sharp boundary. **The atmosphere thins as you travel away from Earth until there are too few gas molecules to detect.**

Pressure Changes To understand the vertical extent of the atmosphere, examine Figure 4, which shows changes in atmospheric pressure with height. Atmospheric pressure is simply the weight of the air above. At sea level, the average pressure is slightly more than 1000 millibars, or slightly more than 1 kilogram per square centimeter. One half of the atmosphere lies below an altitude of 5.6 kilometers. Above 100 kilometers, only 0.00003 percent of all the gases making up the atmosphere exist.

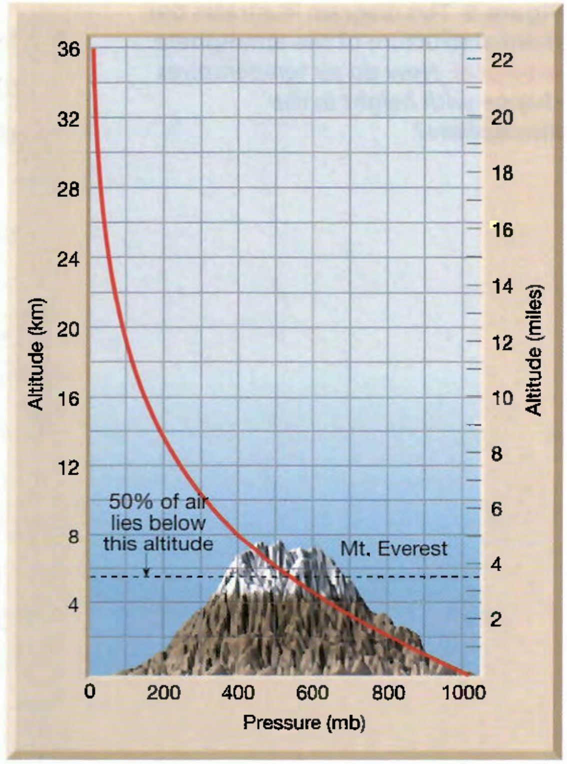


Figure 4 Atmospheric Pressure vs. Altitude This graph shows how atmospheric pressure varies with altitude.
Comparing ***How do changes in air pressure at low altitudes compare with air pressure changes at high altitudes?***

Temperature Changes The pictures of snow-capped mountains rising above snow-free valleys shown in Figure 5 might remind you that Earth's atmosphere becomes colder as you climb higher. But not all layers of the atmosphere show this temperature pattern.

Figure 5 In Jasper National Park in Alberta, Canada, snowy mountaintops contrast with warmer, snow-free lowlands below.

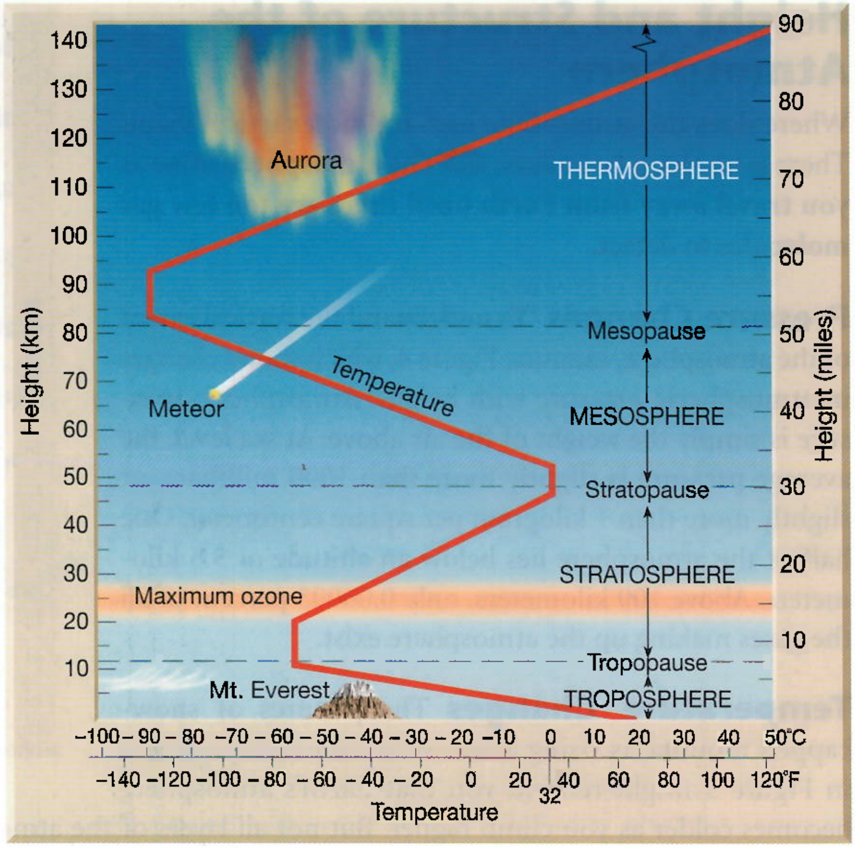


Figure 6 This diagram illustrates the thermal structure of the atmosphere. **Interpret** ***How do air temperatures change with height in the mesosphere?***

The atmosphere can be divided vertically into four layers based on temperature. Figure 6 illustrates these layers. The bottom layer, where temperature decreases with an increase in altitude, is the **troposphere.** It is in this layer that essentially all important weather phenomena occur. The thickness of the troposphere is not the same everywhere. It varies with latitude and the season. On average, the temperature drop continues to a height of about 12 kilometers, where the outer boundary of the troposphere, called the tropopause, is located.

Beyond the tropopause is the **stratosphere.** In the stratosphere, the temperature remains constant to a height of about 20 kilometers. It then begins a gradual increase in temperature that continues until the stratopause, at a height of nearly 50 kilometers above Earth's surface. Temperatures increase in the stratosphere because the atmosphere's ozone is concentrated here. Recall that ozone absorbs ultraviolet radiation from the sun. As a result, the stratosphere is heated.

In the third layer, the **mesosphere,** temperatures again decrease with height until the mesopause. The mesopause is more than 80 kilometers above the surface and the temperatures approach −90°C. The fourth layer extends outward from the mesopause and has no well-defined upper limit. It is the **thermosphere,** a layer that contains only a tiny fraction of the atmosphere's mass. Temperatures increase in the thermosphere because oxygen and nitrogen absorb short-wave, high-energy solar radiation.

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Earth-Sun Relationships

Nearly all of the energy that drives Earth's variable weather and climate comes from the sun. Earth absorbs only a tiny percentage of the energy given off by the sun—less than one two-billionth. This may seem insignificant, but the amount is several hundred thousand times the electrical-generating capacity of the United States.

Solar energy is not distributed evenly over Earth's surface. The amount of energy received varies with latitude, time of day, and season of the year. As you will see, the variations in solar heating are caused by the motions of Earth relative to the sun and by variations in Earth's land and ocean surface. It is the unequal heating of Earth that creates winds and drives the ocean's currents. These movements transport heat from the tropics toward the poles in an attempt to balance energy differences. The results of these processes are the phenomena we call weather.

Earth's Motions Earth has two principal motions—rotation and revolution. Rotation is the spinning of Earth about its axis. The axis is an imaginary line running through the north and south poles. Our planet rotates once every 24 hours, producing the daily cycle of daylight and darkness. Revolution is the movement of Earth in its orbit around the sun. Earth travels at nearly 113,000 kilometers per hour in an elliptical orbit about the sun.

Earth's Orientation We know that it is colder in the winter than in the summer. But why? Length of day and a gradual change in the angle of the noon sun above the horizon affect the amount of energy Earth receives. **Seasonal changes occur because Earth's position relative to the sun continually changes as it travels along its orbit.** Earth's axis is not perpendicular to the plane of its orbit around the sun. Instead it is tilted 23.5 degrees from the perpendicular, as shown in Figure 7. Because the axis remains pointed toward the North Star as Earth moves around the sun, the position of Earth's axis relative to the sun's rays is constantly changing. If the axis were not tilted, we would not have seasonal changes.

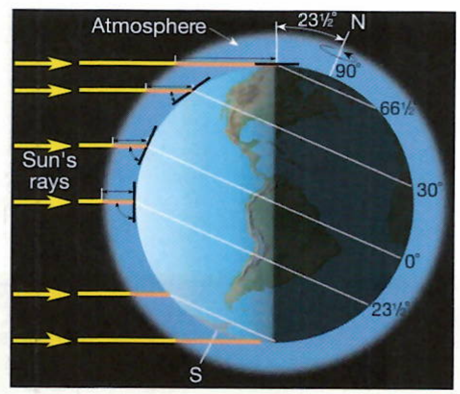


Figure 7 Tilt of Earth's Axis Earth's axis always points toward the North Star as it revolves around the sun.

The orientation of Earth relative to the sun and the constant movement of Earth cause the angle of the noon sun to vary by up to 47 degrees (−23.5 degrees to +23.5 degrees) for many locations during the year. For example, a mid-latitude city like New York, located about 40 degrees north latitude, has a maximum noon sun angle of 73.5 degrees when the sun's vertical rays reach their farthest northward location in June. Six months later, New York has a minimum noon sun angle of 26.5 degrees.

Reading Checkpoint *In which direction does Earth's axis point?*

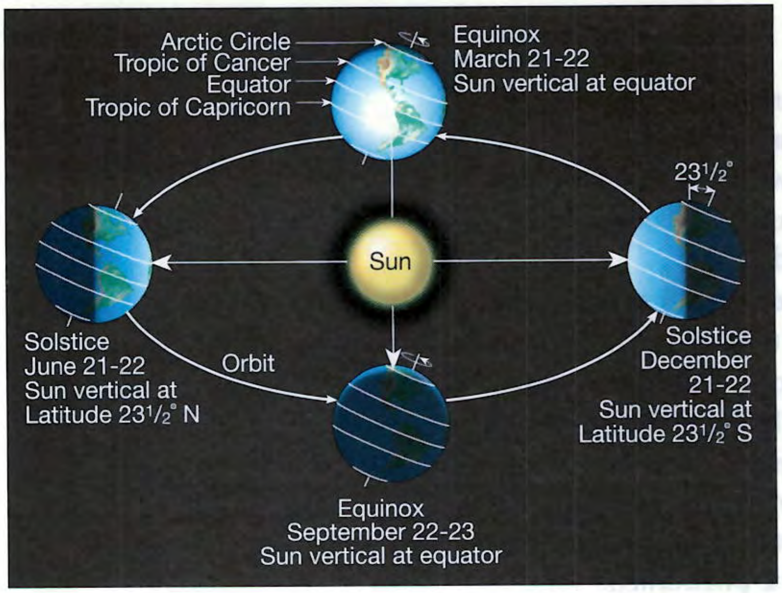


Figure 8 Solstices and equinoxes are important events in Earth's yearly weather cycle.

Solstices and Equinoxes On June 21 or 22 each year the axis is such that the Northern Hemisphere is "leaning" 23.5 degrees toward the sun. This date, shown on the left side of Figure 8, is known as the **summer solstice,** or the first "official" day of summer. Six months later, in December, when Earth has moved to the opposite side of its orbit, the Northern Hemisphere "leans" 23.5 degrees away from the sun. December 21 or 22 is the **winter solstice,** the first day of winter. On days between these extremes, Earth's axis is leaning at amounts less than 23.5 degrees to the rays of the sun.

The equinoxes occur midway between the solstices. September 22 or 23 is the date of the **autumnal equinox** in the Northern Hemisphere. March 21 or 22 is the date of the **spring equinox** for the Northern Hemisphere. On these dates, the vertical rays of the sun strike the equator (0 degrees latitude) because Earth is in a position in its orbit so that the axis is tilted neither toward nor away from the sun.

Length of Daylight The length of daylight compared to darkness also is determined by Earth's position in orbit. All latitudes receive 12 hours of daylight during the vernal and autumnal equinoxes (equal night). The length of daylight on the summer solstice in the Northern Hemisphere is greater than the length of darkness. The farther you are north of the equator on the summer solstice, the longer the period of daylight. When you reach the Arctic Circle, at 66.5 degrees N latitude, the length of daylight is 24 hours.

Section 17.1 Assessment

Reviewing Concepts

1. Compare and contrast weather and climate.
2. Why do seasonal changes occur?
3. How much of Earth's atmosphere is located below about 5.6 kilometers?
4. How do ozone molecules form in the stratosphere?
5. In which layers of the atmosphere does temperature increase with increasing height?

Critical Thinking

6. **Applying Concepts** Explain what would happen to air temperatures in the troposphere if carbon dioxide were removed from air.

Connecting Concepts

Connecting Concepts Using Figure 8, explain why solstices and equinoxes are opposite for the Northern and Southern hemispheres.

17.2 Heating the Atmosphere

Reading Focus

Key Concepts

- How are heat and temperature related?
- What are the three major mechanisms of heat transfer?
- How is the atmosphere affected by each of the heat transfer mechanisms?

Vocabulary

- heat
- temperature
- conduction
- convection
- radiation
- reflection
- scattering
- greenhouse effect

Reading Strategy

Using Prior Knowledge Before you read, copy the table below and write your definition for each vocabulary term. After you read, write the scientific definition of each term and compare it with your original definition.

Term	Your Definition	Scientific Definition
Heat	a. ?	b. ?
Temperature	c. ?	d. ?

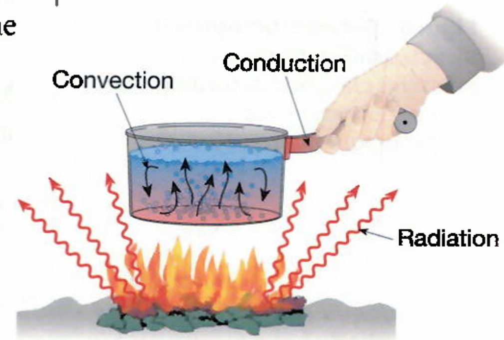
The concepts of heat and temperature often are confused. The phrase "in the heat of the day" is one common expression in which the word "heat" is misused to describe the concept of temperature. **Heat is the energy transferred from one object to another because of a difference in their temperatures.** Recall that all matter is composed of atoms or molecules that possess kinetic energy, or the energy of motion. **Temperature** is a measure of the average kinetic energy of the individual atoms or molecules in a substance. When energy is transferred to the gas atoms and molecules in air, those particles move faster and air temperature rises. When air transfers energy to a cooler object, its particles move slower, and air temperature drops.

Energy Transfer as Heat

Three mechanisms of energy transfer as heat are conduction, convection, and radiation. All three processes, illustrated in Figure 9, happen simultaneously in the atmosphere. These mechanisms operate to transfer energy between Earth's surface (both land and water) and the atmosphere.

Conduction Anyone who has touched a metal spoon that was left in a hot pan has experienced the result of heat conducted through the spoon. **Conduction** is the transfer of heat through matter by molecular activity. The energy of molecules is transferred by collisions from one molecule to another. Heat flows from the higher temperature matter to the lower temperature matter.

Figure 9 Energy Transfer as Heat A pot of water on the campfire illustrates the three mechanisms of heat transfer.



The ability of substances to conduct heat varies greatly. Metals are good conductors, as those of us who have touched hot metal have quickly learned. Air, however, is a very poor conductor of heat. Because air is a poor conductor, conduction is important only between Earth's surface and the air directly in contact with the surface. For the atmosphere as a whole, conduction is the least important mechanism of heat transfer.

Convection Much of the heat transfer that occurs in the atmosphere is carried on by convection. **Convection** is the transfer of heat by mass movement or circulation within a substance. It takes place in fluids, like the ocean and air, where the atoms and molecules are free to move about. Convection also takes place in solids, such as Earth's mantle, that behave like fluids over long periods of time.

The pan of water in Figure 9 shows circulation by convection. Radiation from the fire warms the bottom of the pan, which conducts heat to the water near the bottom of the container. As the water is heated, it expands and becomes less dense than the water above. The warmer water rises because of its buoyancy. At the same time, cooler, denser water near the top of the pan sinks to the bottom, where it becomes heated. As long as the water is heated unequally, it will continue to circulate. In much the same way, most of the heat acquired by radiation and conduction in the lowest layer of the atmosphere is transferred by convective flow.

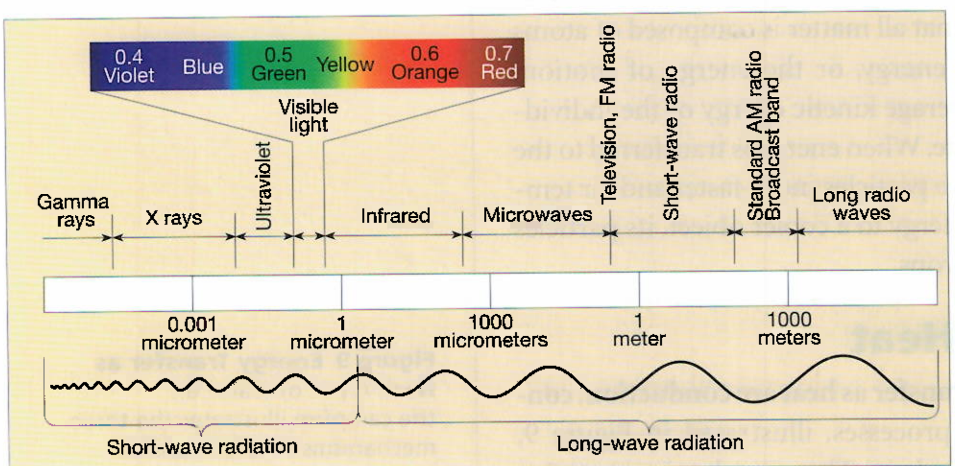


Figure 10 Electromagnetic Spectrum Electromagnetic energy is classified according to wavelength in the electromagnetic spectrum.

Electromagnetic Waves

The sun is the ultimate source of energy that creates our weather. You know that the sun emits light and heat as well as the ultraviolet rays that cause a suntan. These forms of energy are only part of a large array of energy called the electromagnetic spectrum. This spectrum of electromagnetic energy is shown in Figure 10. All radiation, whether X-rays, radio waves, or heat waves, travel through the vacuum of space at 300,000 kilometers per second. They travel only slightly slower through our atmosphere.

Reading Checkpoint *What is convection?*

Imagine what happens when you toss a pebble into a pond. Ripples are made and move away from the location where the pebble hit the water's surface. Much like these ripples, electromagnetic waves move out from their source and come in various sizes. The most important difference among electromagnetic waves is their wavelength, or the distance from one crest to the next. Radio waves have the longest wavelengths, ranging to tens of kilometers. Gamma waves are the shortest, and are less than a billionth of a centimeter long.

Visible light is the only portion of the spectrum you can see. White light is really a mixture of colors. Each color corresponds to a specific wavelength, as shown in Figure 11. By using a prism, white light can be divided into the colors of the rainbow, from violet with the shortest wavelength—0.4 micrometer (1 micrometer is 0.0001 centimeter)—to red with the longest wavelength—0.7 micrometer.

Figure 11 Visible light consists of an array of colors commonly called the colors of the rainbow.

Radiation The third mechanism of heat transfer is radiation. As shown in Figure 9, **radiation** travels out in all directions from its source. **Unlike conduction and convection, which need material to travel through, radiant energy can travel through the vacuum of space.** Solar energy reaches Earth by radiation.

To understand how the atmosphere is heated, it is useful to think about four laws governing radiation.

1. **All objects, at any temperature, emit radiant energy.** Not only hot objects like the sun but also Earth—including its polar ice caps—continually emit energy.
2. **Hotter objects radiate more total energy per unit area than colder objects do.**
3. **The hottest radiating bodies produce the shortest wavelengths of maximum radiation.** For example, the sun, with a surface temperature of nearly 6000°C radiates maximum energy at 0.5 micrometers, which is in the visible range. The maximum radiation for Earth occurs at a wavelength of 10 micrometers, well within the infrared range.
4. **Objects that are good absorbers of radiation are good emitters as well.** Gases are selective absorbers and radiators. The atmosphere does not absorb certain wavelengths of radiation, but it is a good absorber of other wavelengths.

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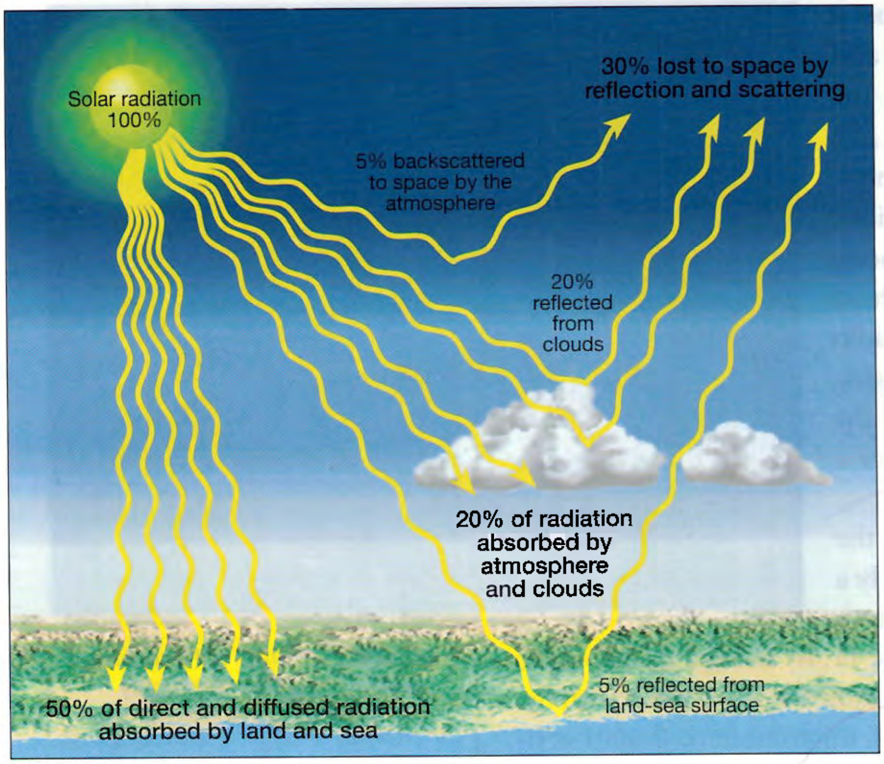


Figure 12 Solar Radiation This diagram shows what happens, on average, to incoming solar radiation by percentage.

What Happens to Solar Radiation?

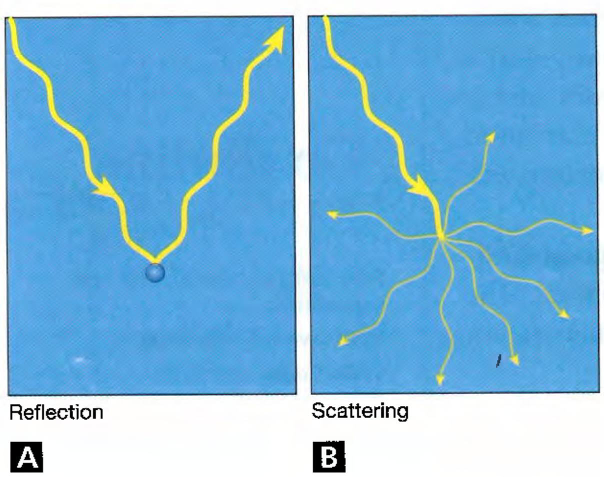
When radiation strikes an object, there usually are three different results.

1. **Some energy is absorbed by the object.** When radiant energy is absorbed, it is converted to heat and causes a temperature increase.
2. **Substances such as water and air are transparent to certain wavelengths of radiation.** These substances transmit the radiant energy. Radiation that is transmitted does not contribute energy to the object.
3. **Some radiation may bounce off the object without being absorbed or transmitted.** Figure 12 shows what happens to incoming solar radiation, averaged for the entire globe.

Reflection and Scattering **Reflection** occurs when light bounces off an object. The reflected radiation has the same intensity as the incident radiation. In contrast, **scattering** produces a larger number of weaker rays that travel in different directions. See Figure 13. Scattering disperses light both forward and backward. However, more energy is dispersed in the forward direction. About 30 percent of the solar energy reaching the outer atmosphere is reflected back to space. This 30 percent also includes the amount of energy sent skyward by scattering. This energy is lost and does not play a role in heating Earth's atmosphere.

Small dust particles and gas molecules in the atmosphere scatter some incoming radiation in all directions. This explains how light reaches into the area beneath a shade tree, and how a room is lit in the absence of direct sunlight. Scattering also accounts for the brightness and even the blue color of the daytime sky. In contrast, bodies like the moon and Mercury—which are without atmospheres—have dark skies and "pitch-black" shadows even during daylight hours. About half of the solar radiation that is absorbed at Earth's surface arrives as scattered light.

Figure 13 Reflection vs. Scattering
A Reflected light bounces back with the same intensity.
B Scattering produces more light rays with a weaker intensity.



Reading Checkpoint *What causes the blue color of the daytime sky?*

Absorption About 50 percent of the solar energy that strikes the top of the atmosphere reaches Earth's surface and is absorbed, as shown in Figure 12. Most of this energy is then reradiated skyward. Because Earth has a much lower surface temperature than the sun, the radiation that it emits has longer wavelengths than solar radiation does.

The atmosphere efficiently absorbs the longer wavelengths emitted by Earth. Water vapor and carbon dioxide are the major absorbing gases. When a gas molecule absorbs light waves, this energy is transformed into molecular motion that can be detected as a rise in temperature. Gases in the atmosphere eventually radiate some of this energy away. Some energy travels skyward, where it may be reabsorbed by other gas molecules. The remainder travels Earthward and is again absorbed by Earth. In this way, Earth's surface is continually being supplied with heat from the atmosphere as well as from the sun.

Without these absorbing gases in our atmosphere, Earth would not be a suitable habitat for humans and other life forms. This important phenomenon has been termed the **greenhouse effect** because it was once thought that greenhouses were heated in a similar manner. A more important factor in keeping a greenhouse warm is the fact that the greenhouse itself prevents the mixing of air inside with cooler air outside. Nevertheless, the term greenhouse effect is still used.

Q&A

Q *Isn't the greenhouse effect responsible for global warming?*

A It is important to note that the greenhouse effect and global warming *are not* the same thing. Without the greenhouse effect, Earth would be uninhabitable. We do have mounting evidence that human activity (particularly the release of carbon dioxide into the atmosphere) is responsible for a rise in global temperatures. Thus, human activities seem to be enhancing an otherwise natural process (the greenhouse effect) to increase Earth's temperature. Nevertheless, to equate the greenhouse effect, which makes life possible, with undesirable changes to our atmosphere caused by human activity is incorrect.

Section 17.2 Assessment

Reviewing Concepts

1. How are heat and temperature related?
2. List and describe the three major mechanisms of heat transfer in the atmosphere.
3. How is the atmosphere affected by
   a. convection?
   b. conduction?
   c. radiation?
4. Describe what happens to solar radiation when it strikes an object.
5. Contrast reflection and scattering.

Critical Thinking

6. **Applying Concepts** Dark objects tend to absorb more radiation than light-colored objects. Explain whether dark objects or light objects on Earth's surface would be better radiators of heat.

Writing in Science

Descriptive Paragraph Write a paragraph that describes the four laws governing radiation discussed in this chapter. Make sure to use your own words. Use examples to reinforce concepts wherever possible.

17.3 Temperature Controls

Reading Focus

Key Concepts

- What is a temperature control?
- How do the heating of land and water differ?
- Why do some clouds reflect a portion of sunlight back to space?

Vocabulary

- albedo
- isotherm

Reading Strategy

Previewing Copy the table below. Before you read, use Figure 15 to describe the temperature variations for Vancouver and Winnipeg.

Temperature Variations	
Vancouver	a. ___?___
Winnipeg	b. ___?___

Figure 14 This modern instrument shelter contains an electrical thermometer called a thermistor.

Temperature is one of the basic elements of weather and climate. When someone asks what it is like outside, air temperature is often the first element we mention. At a weather station, the temperature is read on a regular basis from instruments mounted in an instrument shelter like the one in Figure 14. The shelter protects the instruments from direct sunlight and allows a free flow of air.

Why Temperatures Vary

A temperature control is any factor that causes temperature to vary from place to place and from time to time. Earlier in this chapter you examined the most important cause for temperature variations—differences in the receipt of solar radiation. Because variations in the angle of the sun's rays and length of daylight depend on latitude, they are responsible for warmer temperatures in the tropics and colder temperatures toward the poles. Seasonal temperature changes happen as the sun's vertical rays move toward and away from a particular latitude during the year. **Factors other than latitude that exert a strong influence on temperature include heating of land and water, altitude, geographic position, cloud cover, and ocean currents.**

Reading Checkpoint *List three factors that influence temperature.*

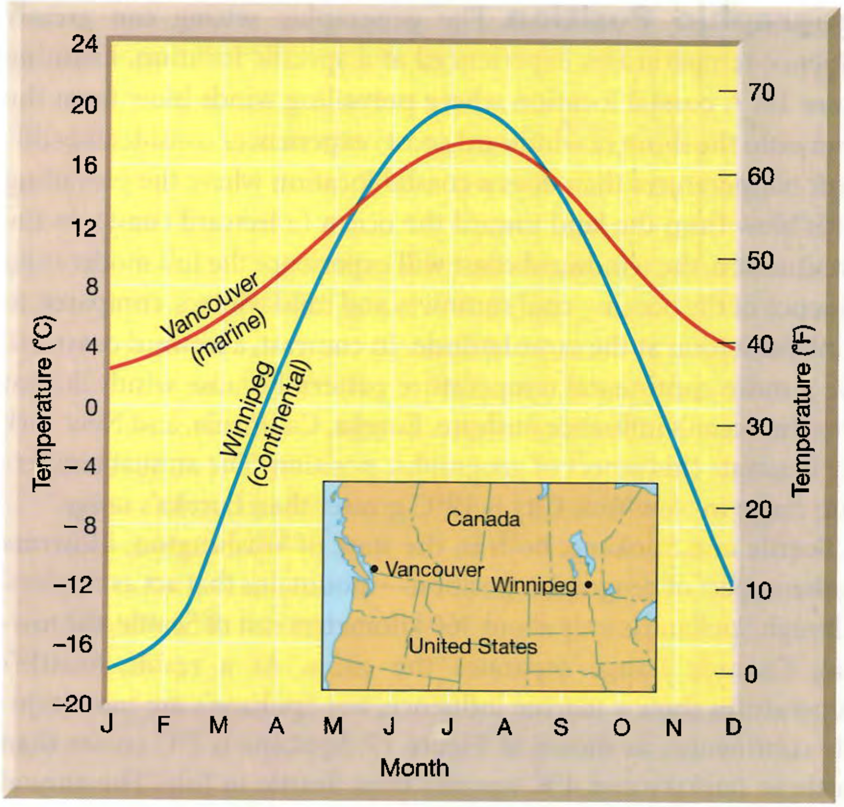


Figure 15 Mean Monthly Temperatures for Vancouver and Winnipeg Winnipeg illustrates the greater extremes associated with an interior location.
Calculating ***How much lower is Winnipeg's January mean temperature than Vancouver's? Calculate the temperature to the nearest degree.***

Land and Water The heating of Earth's surface controls the temperature of the air above it. To understand variations in air temperature, we consider the characteristics of the surface. Different land surfaces absorb varying amounts of incoming solar energy. The largest contrast, however, is between land and water. **Land heats more rapidly and to higher temperatures than water. Land also cools more rapidly and to lower temperatures than water.** Temperature variations, therefore, are considerably greater over land than over water.

Monthly temperature data for two cities, shown in Figure 15, show the influence of a large body of water. Vancouver, British Columbia, is located along the windward Pacific coast. Winnipeg, Manitoba, is far from the influence of water. Both cities are at about the same latitude, so they experience similar lengths of daylight and angles of the sun's rays. Winnipeg, however, has much greater temperature extremes than Vancouver does. Vancouver's moderate year-round climate is due to its location by the Pacific Ocean.

Temperature variations in the Northern and Southern hemispheres are compared in Table 1. Water accounts for 61 percent of the Northern Hemisphere, and land accounts for the remaining 39 percent. In the Southern Hemisphere, 81 percent of the surface is water and only 19 percent of the surface is land. The Southern Hemisphere shows smaller annual temperature variations.

Table 1 Variation in Annual Mean Temperature Range (°C) with Latitude

Latitude	Northern Hemisphere	Southern Hemisphere
0	0	0
15	3	4
30	13	7
45	23	6
60	30	11
75	32	26
90	40	31

Geographic Position The geographic setting can greatly influence temperatures experienced at a specific location. Examine Figure 16. A coastal location where prevailing winds blow from the ocean onto the shore (a windward coast) experiences considerably different temperatures than does a coastal location where the prevailing winds blow from the land toward the ocean (a leeward coast). In the first situation, the windward coast will experience the full moderating influence of the ocean—cool summers and mild winters, compared to an inland station at the same latitude. In contrast, a leeward coast will have a more continental temperature pattern because winds do not carry the ocean's influence onshore. Eureka, California, and New York City illustrate this aspect of geographic position. The annual temperature range in New York City is 19°C greater than Eureka's range.

Seattle and Spokane, both in the state of Washington, illustrate another aspect of geographic position—mountains that act as barriers. Although Spokane is only about 360 kilometers east of Seattle, the towering Cascade Range separates the cities. As a result, Seattle's temperatures show a marine influence, but Spokane's are more typically continental, as shown in Figure 17. Spokane is 7°C cooler than Seattle in January and 4°C warmer than Seattle in July. The annual range in Spokane is 11°C greater than in Seattle. The Cascade Range cuts Spokane off from the moderating influence of the Pacific Ocean.

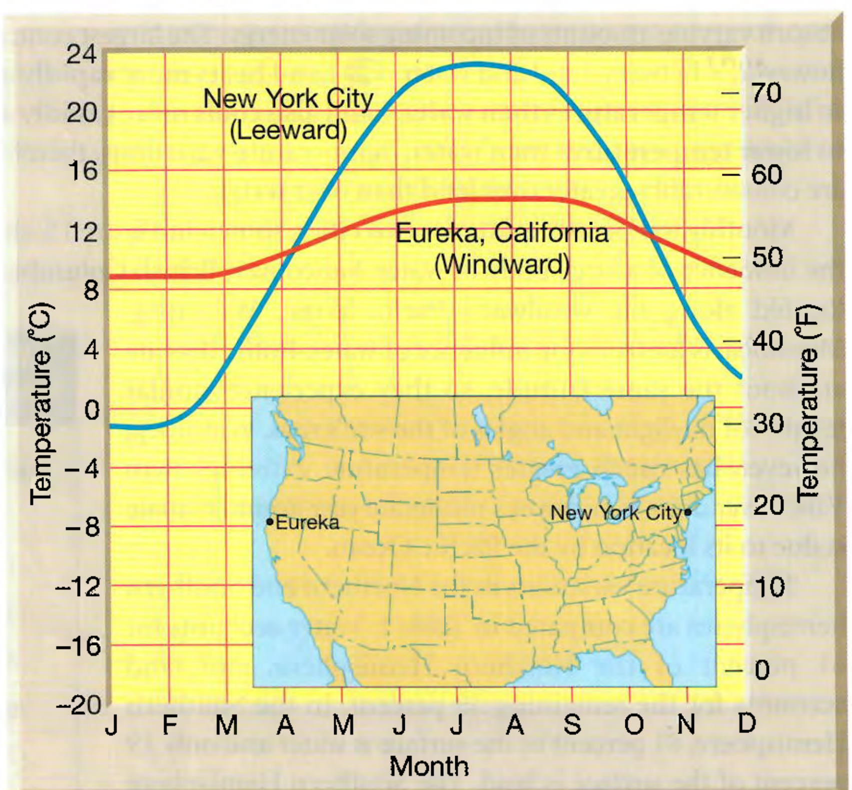


Figure 16 Mean Monthly Temperatures for Eureka and New York City Eureka is strongly influenced by prevailing ocean winds, and New York City is not.

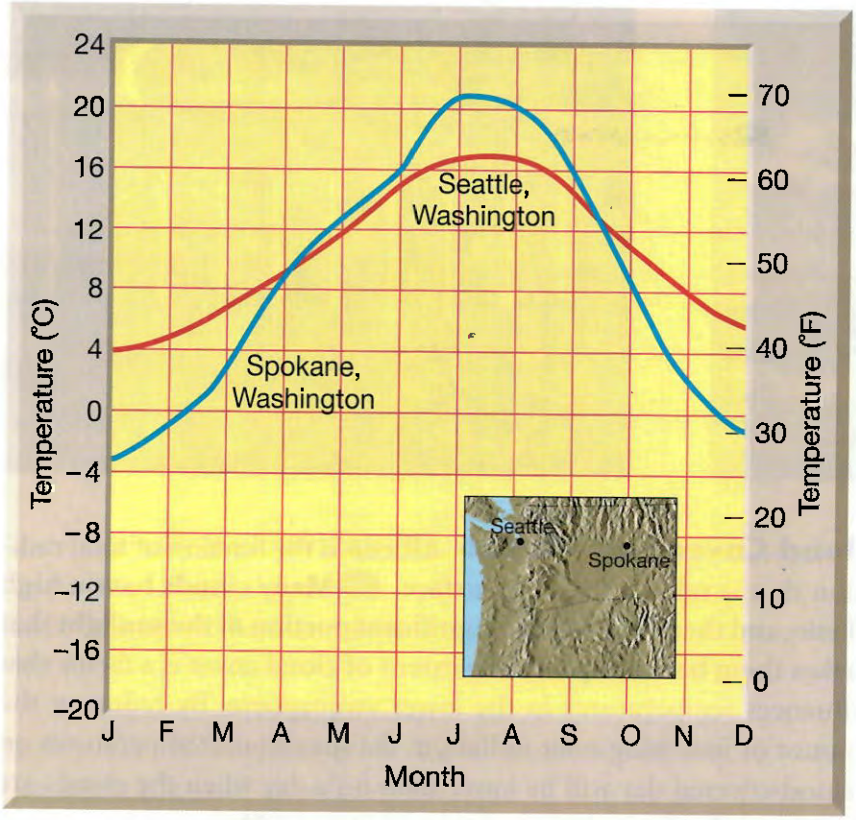
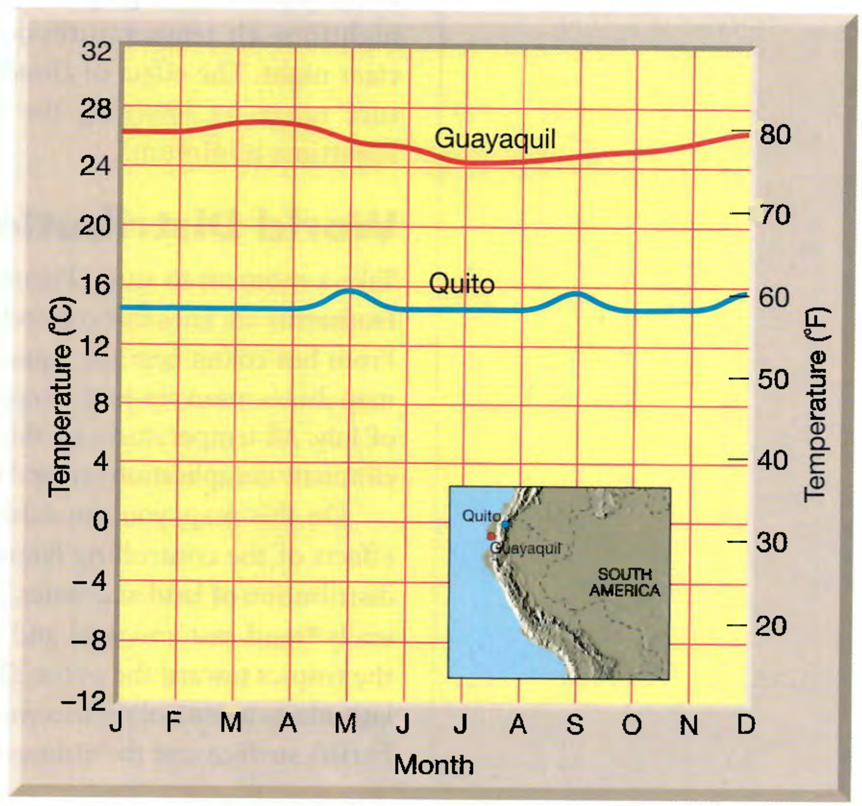


Figure 17 Mean Monthly Temperatures for Seattle and Spokane The Cascade Mountains cut off Spokane from the moderating influence of the Pacific Ocean. **Relating Cause and Effect** ***How does this affect Spokane's annual temperature range?***

Figure 18 Mean Monthly Temperatures for Quito and Guayaquil Quito's altitude is much higher than Guayaquil's, causing Quito to experience cooler temperatures than Guayaquil.

Altitude Two cities in Ecuador, Quito and Guayaquil, demonstrate the influence of altitude on mean temperature. Both cities are near the equator and relatively close to one another, as shown in Figure 18. The annual mean temperature at Guayaquil is 25°C, compared to Quito's mean of 13°C. If you note these cities' elevations, you can understand the temperature difference. Guayaquil is only 12 meters above sea level, whereas Quito is high in the Andes Mountains at 2800 meters.



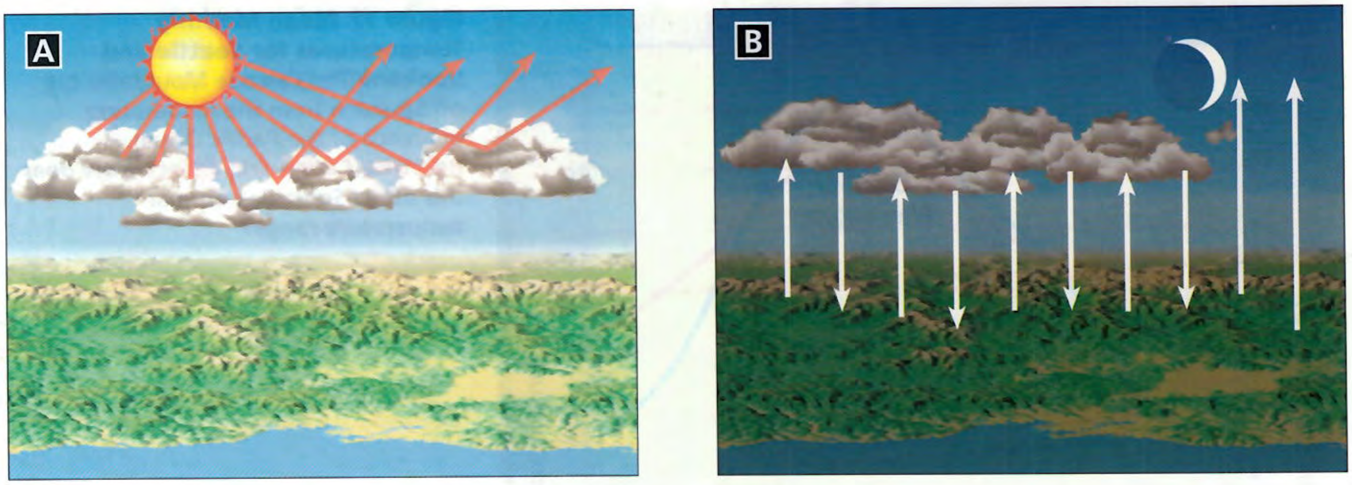


Figure 19 **A** During daylight hours, clouds reflect solar radiation back to space. **B** At night, clouds absorb radiation from the land and reradiate some of it back to Earth, increasing nighttime temperatures.

Cloud Cover and Albedo **Albedo** is the fraction of total radiation that is reflected by any surface. **Many clouds have a high albedo, and therefore reflect a significant portion of the sunlight that strikes them back to space.** The extent of cloud cover is a factor that influences temperatures in the lower atmosphere. By reducing the amount of incoming solar radiation, the maximum temperatures on a cloud-covered day will be lower than on a day when the clouds are absent and the sky is clear, as shown in Figure 19A.

At night, clouds have the opposite effect, as shown in Figure 19B. Clouds act as a blanket by absorbing outgoing radiation emitted by Earth and reradiating a portion of it back to the surface. Thus, cloudy nighttime air temperatures do not drop as low as they would on a clear night. The effect of cloud cover is to reduce the daily temperature range by lowering the daytime maximum and raising the nighttime minimum.

World Distribution of Temperature

Take a moment to study Figure 20, which is a world isothermal map. **Isotherms** are lines that connect points that have the same temperature. From hot colors near the equator to cool colors toward the poles, this map shows mean sea-level temperatures in the seasonally extreme month of July. All temperatures on this map have been reduced to sea level to eliminate complications caused by differences in altitude.

On this map, you can study global temperature patterns and the effects of the controlling factors of temperature, especially latitude, distribution of land and water, and ocean currents. The isotherms generally trend east and west and show a decrease in temperatures from the tropics toward the poles. This map emphasizes the importance of latitude as a control on incoming solar radiation, which in turn heats Earth's surface and the atmosphere above it.

World Isothermal Map

MAP MASTER™ Skills Activity

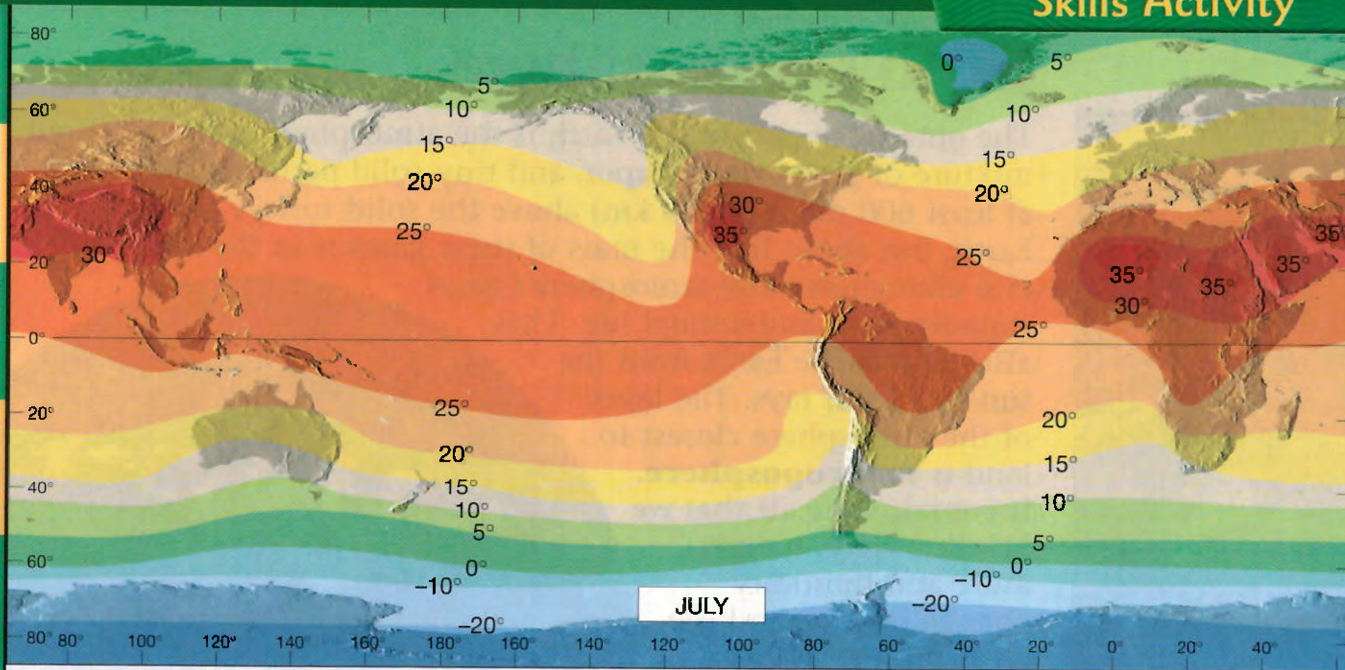


Figure 20

Regions The map shows the distribution of world mean sea-level temperatures averaged for the month of July.
Locating Estimate the latitude range for temperatures between 20 and 25 degrees Celsius in the Northern Hemisphere. Approximate to the nearest 5 degrees latitude for each extreme.
Predicting Do you expect the color of the temperature band to change near the equator for the month of January? Explain your prediction.

Section 17.3 Assessment

Reviewing Concepts

1. What is a temperature control?
2. How do the heating of land and water differ?
3. Why do many clouds reflect a significant amount of sunlight back to space?
4. Why do some coastal cities experience a moderation of temperature from water, while others do not?
5. List four specific controls of atmospheric temperature.

49/50
50

Critical Thinking

6. **Inferring** Look back at the graph in Figure 18. Why do the temperatures of these two cities stay within a limited range throughout the year?

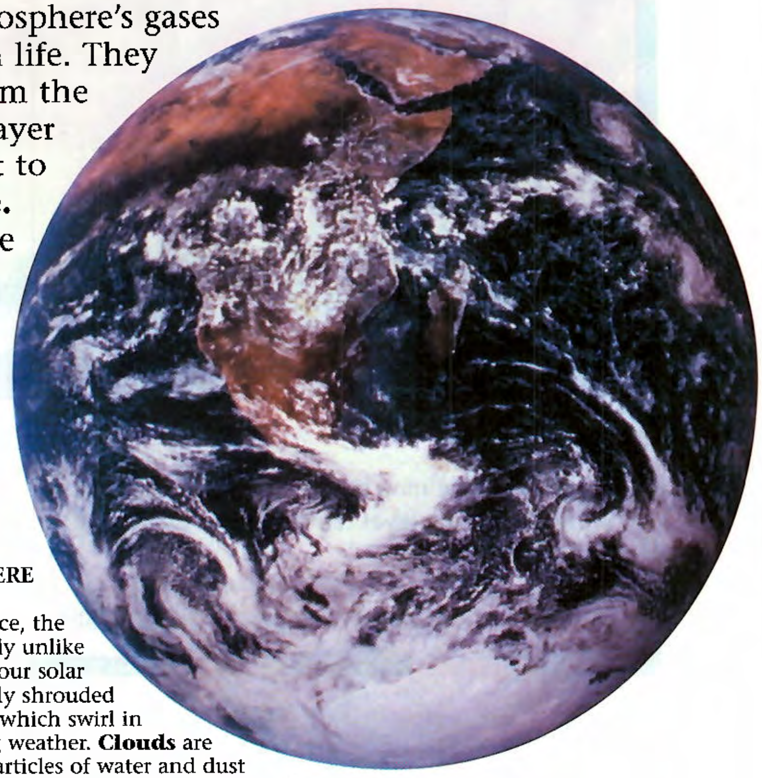
Math Practice

7. Using the data in Table 1, determine the latitude that shows the greatest variation in average mean temperature between the Northern and Southern Hemispheres.

How the Earth Works

Earth's Atmosphere

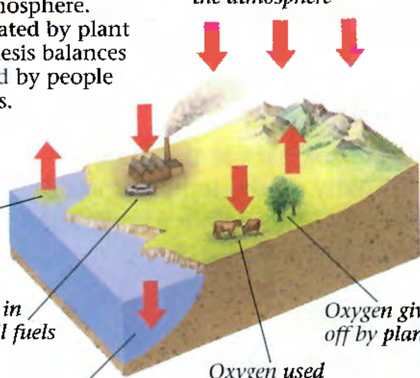
The outermost part of the Earth is the atmosphere, a multilayered mixture of gases, water vapor, and tiny solid particles. It extends at least 600 miles (1,000 km) above the solid surface of the Earth, but about half the mass of these gases is in the lowest (5.6 kilometers). The atmosphere's gases support plant and animal life. They also protect the Earth from the sun's harmful rays. The layer of the atmosphere closest to land is the **troposphere.** It contains the air that we breathe. Here, temperature and humidity change rapidly, and the air is turbulent, creating weather patterns.



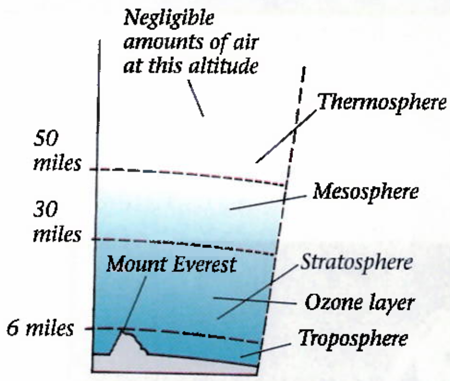
OXYGEN FROM PHOTOSYNTHESIS
Oxygen is a relative newcomer in the Earth's atmosphere. It has come from plants that, during **photosynthesis,** use carbon dioxide to make their food, while giving out oxygen. The earliest photosynthesizing plants, which probably looked like these algae, evolved about 3,500 million years ago.

THE ATMOSPHERE FROM SPACE
Viewed from space, the Earth looks totally unlike other planets of our solar system. It is partly shrouded in white clouds, which swirl in patterns, making weather. **Clouds** are masses of tiny particles of water and dust floating in the atmosphere. A very low cloud is called fog.

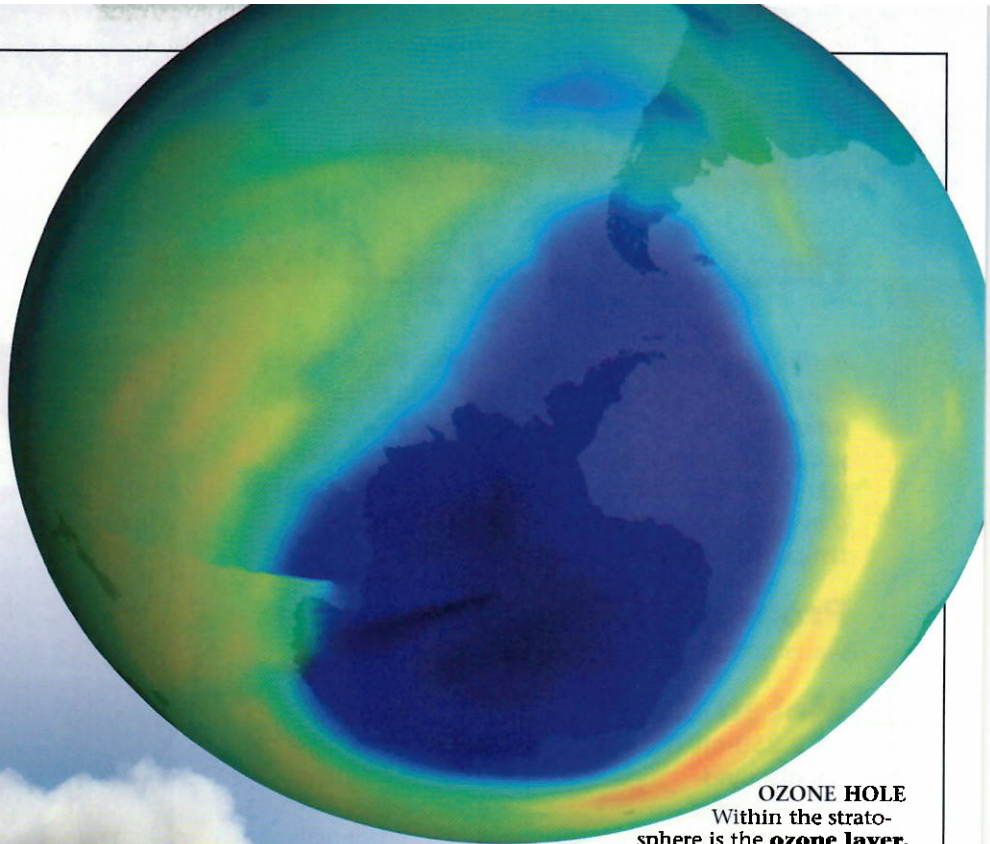
OXYGEN CYCLE
A vast store of oxygen exists in oceans, rocks, and the atmosphere. Oxygen created by plant photosynthesis balances oxygen used by people and animals.



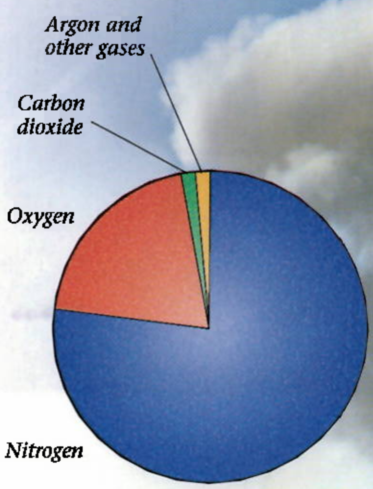
FERTILE LAND
The atmosphere helps life to flourish on the Earth. It offers protection from harmful radiations and provides nourishment for both plants and animals. Winds in the troposphere moderate daily and seasonal temperatures by distributing heat around the world.



LAYERS OF ATMOSPHERE
The Earth's atmosphere has several layers. The heights of these layers vary with season and latitude. Weather is confined to the troposphere, and almost all clouds are below this level. In the stratosphere lies the important ozone layer that filters the sun's rays.

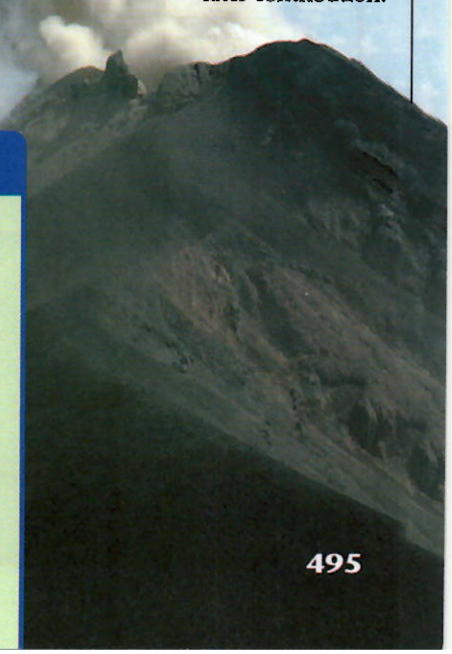


OZONE HOLE
Within the stratosphere is the **ozone layer,** a band of ozone gas that absorbs the sun's harmful ultraviolet rays. In recent years, the ozone layer has been getting thinner. Certain pollutant gases, such as chlorofluorocarbons, cause ozone molecules to break down. Some scientists suggest that ozone depletion also may be caused by natural phenomena. Holes in the ozone layer were first detected over Antarctica and the Arctic. At times, the southern hole has expanded over populated areas of South America, as shown by the dark blue color in this NASA satellite photograph.



GASES IN THE ATMOSPHERE
The most abundant gas in the lower atmosphere is nitrogen, which makes up about 78 percent of air. Oxygen, about 21 percent of air, is essential for supporting animal life. Carbon dioxide is just a tiny fraction of the atmosphere, but it is vital in sustaining plant life.

VOLCANIC GASES
About 4 billion years ago, the Earth had no atmosphere and its surface was covered with erupting volcanoes. The Earth's atmosphere was formed mostly from gases spewed out by volcanoes since the Earth began, although some gases, like oxygen, are a later contribution.



ASSESSMENT

1. **Key Terms** Define **(a)** troposphere, **(b)** photosynthesis, **(c)** cloud, **(d)** ozone layer.
2. **Physical Processes** How was the earth's atmosphere formed?
3. **Natural Resources** How does carbon dioxide support life?
4. **Geographic Tools** How does the NASA satellite photograph display the growing problem of ozone holes?
5. **Critical Thinking Analyzing Processes** Study the diagram showing the oxygen cycle. **(a)** How would extensive deforestation affect the oxygen cycle? **(b)** Which part of the cycle can damage the ozone layer?

Exploration Lab

Heating Land and Water

In this lab you will model the difference in the heating of land and water when it is subjected to a source of radiation. You first will assemble simple tools. Then you will observe and record temperature data. Finally, you will explain the results of the experiment and how they relate to the moderating influence of water on air temperatures near Earth's surface.

Problem How do the heating of land and water compare?

Materials

- 2 250-mL beakers
- dry sand
- tap water
- ring stand
- light source
- 2 flat wooden sticks
- 2 thermometers
- graph paper
- 3 colored pencils

Skills Modeling, Observing, Measuring, Analyzing Data

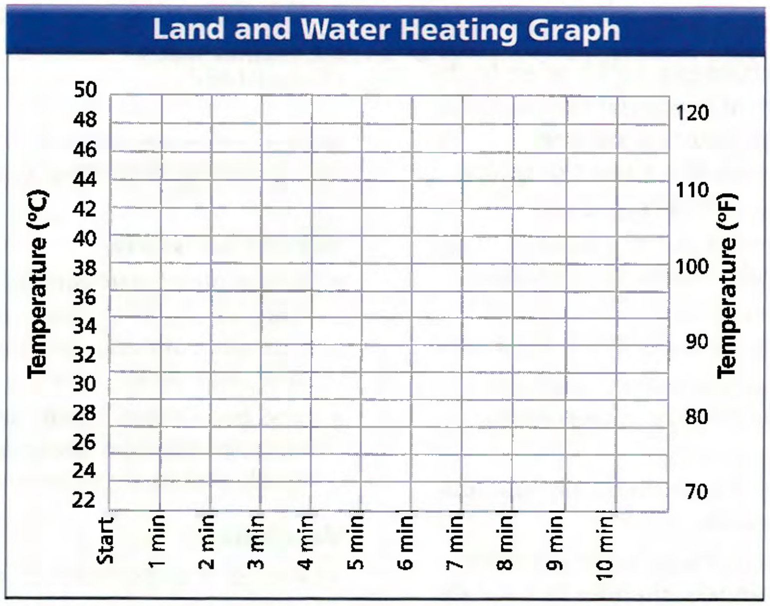
Procedure

Part A: Preparing for the Experiment

1. On a separate sheet of paper, copy the data table shown.
2. Pour 200 mL of dry sand into one of the beakers. Pour 200 mL of water into the other beaker.

Land and Water Heating Data Table

	Starting Temperature	1 min	2 min	3 min	4 min	5 min	6 min	7 min	8 min	9 min	10 min
Water											
Dry sand											
Damp sand											



3. Hang a light source from a ring stand so that it is about 5 inches above the beaker of sand and the beaker of water. The light should be situated so that it is at the same height above both beakers.
4. Using the wooden sticks, suspend a thermometer in each beaker. The thermometer bulbs should be just barely below the surfaces of the sand and the water.
5. Record the starting temperatures for both the dry sand and the water in the data table.

Part B: Heating the Beakers

CAUTION *Do not touch the light source or the beakers without using thermal mitts.*

6. Turn on the light. Observe and record the temperatures in the data table at one-minute intervals for 10 minutes.
7. Turn off the light for several minutes. Dampen the sand with water and record the starting temperature for damp sand. Repeat step 6 for the damp sand.

Analyze and Conclude

1. **Using Tables and Graphs** Copy the sample land and water heating graph sheet onto a separate piece of graph paper. Use the data you collected to plot the temperatures for the water, dry sand, and damp sand. Use a different color line to connect the points for each material.
2. **Comparing and Contrasting** How does the changing temperature differ for dry sand and water when they are exposed to equal amounts of radiation?
3. **Comparing and Contrasting** How does the changing temperature differ for dry sand and damp sand when they are exposed to equal amounts of radiation?
4. **Applying** Locate Eureka, California, and Lafayette, Indiana, on a map. Infer which city would show the greatest annual temperature range. Explain your answer.

CHAPTER 17

Study Guide

17.1 Atmosphere Characteristics

Key Concepts

- Weather is constantly changing, and it refers to the state of the atmosphere at any given time or place. Climate is the sum of all statistical weather information that helps describe a place or region.
- Water vapor is the source of all clouds and precipitation. Like carbon dioxide, it absorbs heat given off by Earth as well as some solar energy.
- If ozone did not filter most UV radiation, Earth would be uninhabitable for many living organisms.
- The atmosphere thins as you travel away from Earth, until there are too few gas molecules to detect.
- The atmosphere can be divided vertically into four layers based on temperature.
- Seasonal changes occur because Earth's position relative to the sun continually changes as it travels along its orbit.

Vocabulary

ozone, *p. 478;* troposphere, *p. 480;* stratosphere, *p. 480;* mesosphere, *p. 480;* thermosphere, *p. 480;* summer solstice, *p. 482;* winter solstice, *p. 482;* autumnal equinox, *p. 482;* spring equinox, *p. 482*

17.2 Heating the Atmosphere

Key Concepts

- Heat is the transfer of energy between two objects resulting from differences in their temperatures. Temperature is a measure of the average kinetic energy of individual particles.
- Three mechanisms of heat transfer are conduction, convection, and radiation. Unlike conduction and convection, radiant energy can travel through the vacuum of space.
- All objects, at any temperature, emit radiant energy. Hotter objects radiate more total energy per unit area than colder objects do. The hottest radiating bodies produce the shortest wavelengths of maximum radiation. Objects that are good absorbers of radiation are good emitters as well.
- Objects can absorb, transmit, scatter, or reflect radiation that strikes them.

Vocabulary

heat, *p. 483;* temperature, *p. 483;* conduction, *p. 483;* convection, *p. 484;* radiation, *p. 485;* reflection, *p. 486;* scattering, *p. 486;* greenhouse effect, *p. 487*

17.3 Temperature Controls

Key Concepts

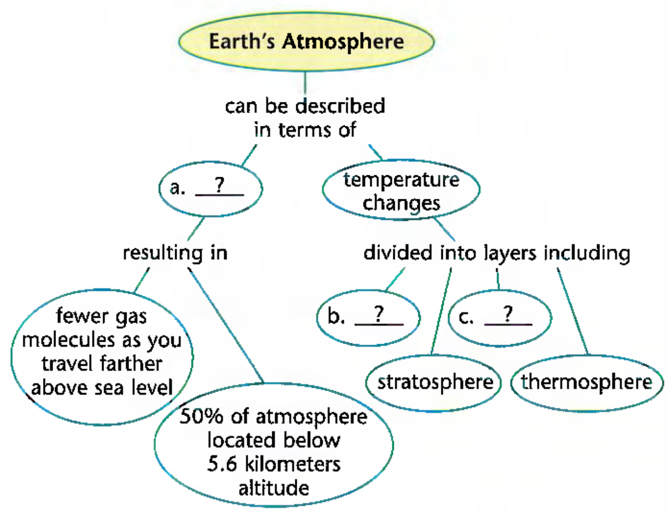
- Factors other than latitude that exert a strong influence on temperature include heating of land and water, altitude, geographic position, cloud cover, and ocean currents.
- Land heats more rapidly and to higher temperatures than water. Land also cools more rapidly and to lower temperatures than water.

Vocabulary

albedo, *p. 492;* isotherm, *p. 492*

Thinking Visually

Concept Map Copy the concept map below onto a sheet of paper. Use information from the chapter to complete the concept map.



CHAPTER 17

Assessment

Interactive textbook with assessment at PHSchool.com

Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. What is a description of atmospheric conditions over a long period of time?
a. climate **b.** meteorology
c. precipitation **d.** weather

2. The bottom layer of the atmosphere in which we live is called the
a. mesosphere. **b.** stratosphere.
c. thermosphere. **d.** troposphere.

3. Which form of radiation has the longest wavelength?
a. blue light **b.** infrared
c. radio waves **d.** ultraviolet

4. This layer of atmosphere contains ozone that filters UV radiation.
a. mesosphere **b.** stratosphere
c. thermosphere **d.** troposphere

5. The average kinetic energy of all the atoms and molecules that make up a substance is referred to as
a. radiation. **b.** greenhouse effect.
c. temperature. **d.** heat.

6. The two principle absorbers of radiation emitted by Earth's surface are carbon dioxide and
a. nitrogen. **b.** oxygen.
c. ozone. **d.** water vapor.

7. On a map showing temperature distributions, what are the lines connecting points of equal temperature?
a. isobars **b.** isotemps
c. isotherms **d.** equigrads

8. Which gas is most abundant in clean, dry air?
a. argon **b.** carbon dioxide
c. nitrogen **d.** oxygen

9. Select the best description of air.
a. It is a compound.
b. It is an element.
c. It is a mixture.
d. It is mainly oxygen and carbon dioxide.

10. Earth's atmosphere is thought to have become enriched in which gas about 2.5 billion years ago?
a. argon **b.** carbon dioxide
c. nitrogen **d.** oxygen

Understanding Concepts

11. Why are temperature variations greater over dry land than they are over water?

12. Describe how the ozone in the stratosphere forms.

13. Describe the three types of heat transfer in the atmosphere.

14. In what ways can geographic position be considered a temperature control?

15. Describe the two principle motions of Earth.

16. Explain why Earth's atmosphere is mainly heated from the ground up.

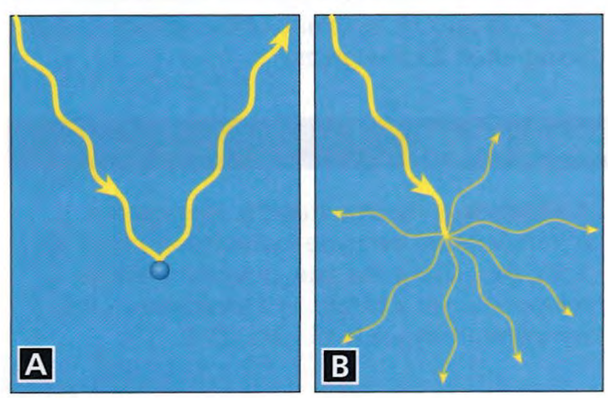
17. Describe the effects of cloud cover on air temperature.

18. Why do temperatures increase in the stratosphere?

19. What causes the position of the noon sun to vary by up to 47 degrees over a year's time?

Use the figure below to answer Question 20.

20. The illustration below shows two ways that radiation bounces off objects. Identify the process shown in each diagram. What clues in the illustration helped you identify these processes?



CHAPTER 17

Assessment *continued*

Critical Thinking

Use the table below to answer Questions 21 and 22.

Albedo of Various Surfaces

Surface	Percent Reflected
Clouds, stratus	
<meters thick	25–63
150–300 meters thick	45–75
300–600 meters thick	59–84
Average of all types and thicknesses	50–55
Concrete	17–27
Crops, green	5–25
Forest, green	5–10
Meadows, green	5–25
Ploughed field, moist	14–17
Road, blacktop	5–10
Sand, white	30–60
Snow, fresh-fallen	80–90
Snow, old	45–70
Soil, dark	5–15
Soil, light (or desert)	25–30
Water	8*

*Typical albedo value for a water surface. The albedo of a water surface varies greatly depending upon the sun angle.

21. **Analyzing Data** Using the data in the table, determine which types of surfaces have the highest average albedos.

22. **Applying Concepts** Determine the date after which the length of daylight gets progressively longer going south from the equator. Use Figure 8 to explain your answer.

23. **Inferring** Give an example of how the Earth system might be affected if Earth's axis were perpendicular to the plane of its orbit instead of being tilted 23.5 degrees.

Math Skills

24. **Calculating** Assume that the average rate of temperature decrease in the troposphere is 6.5°C/km. Using this rate, determine the air temperature at a height of 2 kilometers if the temperature at sea level were 23°C.

Concepts in Action

25. **Inferring** Yakutsk is located in Siberia at about 60 degrees north latitude. This Russian city has one of the highest average annual temperature ranges in the world: 62.2°C. Explain the reasons for the very high annual temperature range.

26. **Making Generalizations** Speculate on the changes in global temperatures that might occur if Earth had substantially more land area and less ocean area than it does at present. How might such changes influence the biosphere?

27. **Applying Concepts** Why are carbon dioxide and water vapor such important components in Earth's atmosphere? What would happen to life forms on Earth if these gases were no longer present in the atmosphere?

28. **Generalizing** State the relationship between the temperature of a radiating body and the wavelengths of radiation that it emits.

29. **Interpreting Illustrations** Refer to Figure 20. What can you determine about temperatures in regions where isotherms are closely spaced, compared with regions where isotherms are farther apart?

30. **Writing in Science** Write a paragraph that describes two environmental settings where you would expect the albedo of surfaces to be high. Your scenarios can describe any reasonable area on Earth's surface. Be sure to include as much detail as possible in your paragraph.

Performance-Based Assessment

Designing an Experiment Design and conduct an experiment that models how variations in color of an object can affect the amount of radiation it absorbs. As a first step, write a clear hypothesis statement. Then plan the materials you will need to design the experiment. Have your teacher approve your plan before you begin.

Standardized Test Prep

Test-Taking Tip

Sometimes all the response choices to a test question look similar. For example, they might have the same prefix or suffix. When all of the answer choices are similar, try answering the question BEFORE looking at the answers. Once you have answered the test item yourself, then look for the answer choice that agrees with your answer. Look for words that are correct words, but do not belong with the others.

The transfer of heat through matter by molecular activity occurs in

(A) convection.
(B) conduction.
(C) radiation.
(D) reflection.

(Answer: B)

Choose the letter that best answers the question or completes the statement.

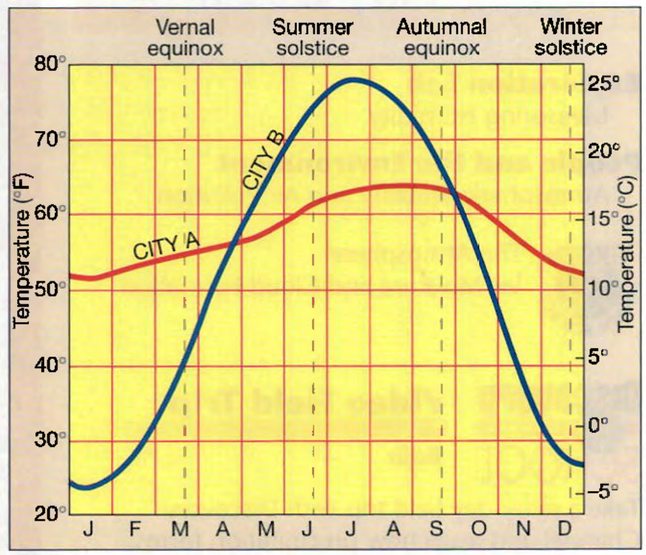
1. Which of these gases plays a more important role in weather processes than the others?
   (A) argon
   (B) carbon dioxide
   (C) nitrogen
   (D) oxygen

2. Practically all clouds and storms occur in this layer of the atmosphere.
   (A) mesosphere
   (B) stratosphere
   (C) thermosphere
   (D) troposphere

3. The primary wavelengths of radiation emitted by Earth's surface are
   (A) longer than those emitted by the sun.
   (B) shorter than those emitted by the sun.
   (C) about the same as those emitted by the sun.
   (D) about the same as UV radiation.

4. Which of the following is true about equinoxes?
   (A) They occur in June and December.
   (B) The sun's vertical rays are striking either the Tropic of Cancer or the Tropic of Capricorn.
   (C) Lengths of daylight and darkness are equal everywhere.
   (D) The length of daylight in the Arctic and Antarctic Circles is 24 hours.

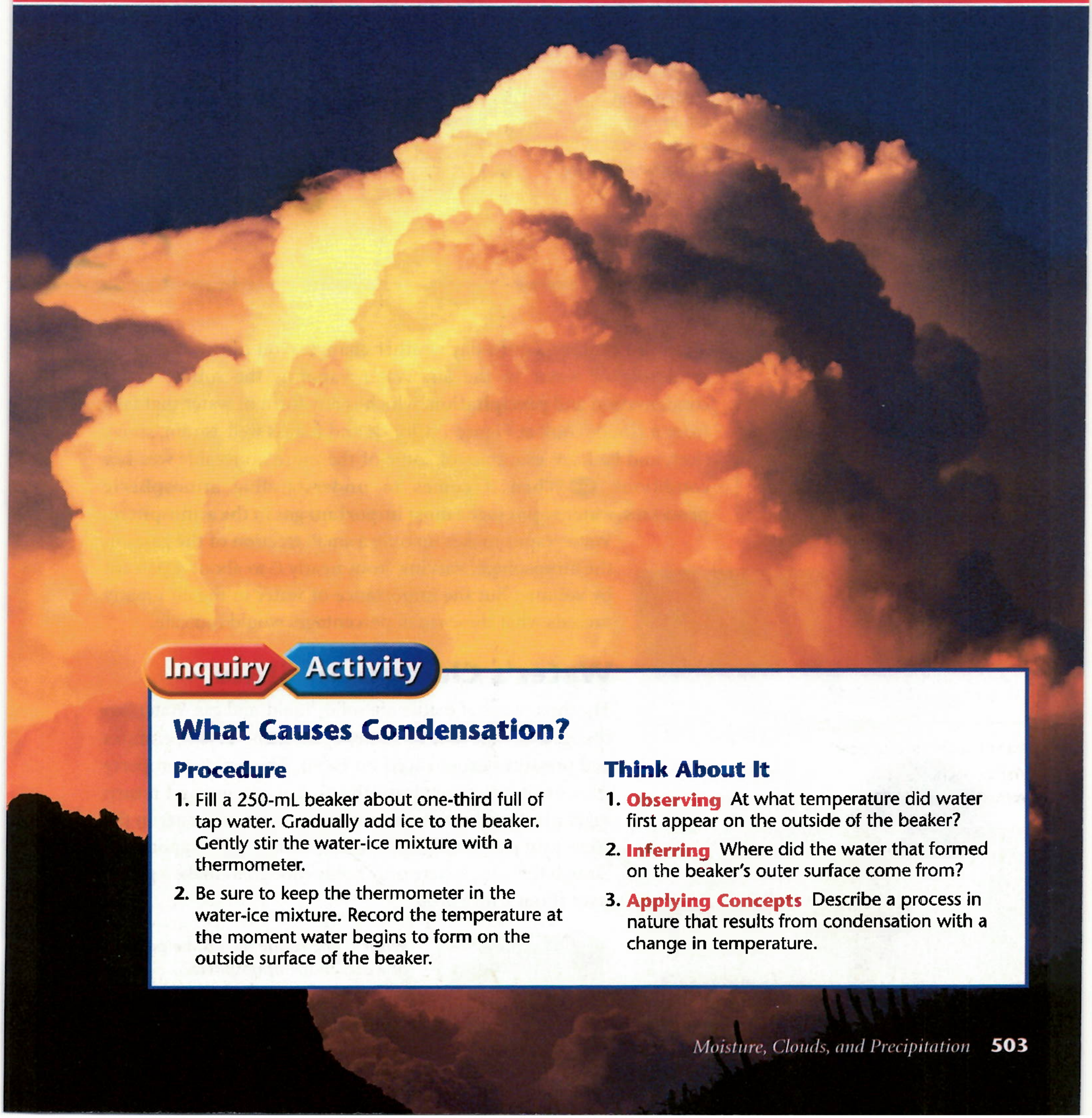
Use the graph below to answer Questions 5 and 6.



5. Determine the difference in December mean temperatures for cities A and B. Express your answer to the nearest degree C.

6. In which hemisphere are the cities located? Use information given in the graph to explain your answer.

Chapter Preview



Inquiry Activity

What Causes Condensation?

Procedure

1. Fill a 250-mL beaker about one-third full of tap water. Gradually add ice to the beaker. Gently stir the water-ice mixture with a thermometer.
2. Be sure to keep the thermometer in the water-ice mixture. Record the temperature at the moment water begins to form on the outside surface of the beaker.

Think About It

1. **Observing** At what temperature did water first appear on the outside of the beaker?
2. **Inferring** Where did the water that formed on the beaker's outer surface come from?
3. **Applying Concepts** Describe a process in nature that results from condensation with a change in temperature.

18.1 Water in the Atmosphere

Reading Focus

Key Concepts

- Which gas is most important for understanding atmospheric processes?
- What happens during a change of state?
- How do warm and cold air compare in their ability to hold water vapor?
- What is relative humidity?
- What can change the relative humidity of air?

Vocabulary

- precipitation
- latent heat
- evaporation
- condensation
- sublimation
- deposition
- humidity
- saturated
- relative humidity
- dew point
- hygrometer

Reading Strategy

Monitoring Your Understanding Before you read, copy the table. List what you know about water in the atmosphere and what you would like to learn. After you read, list what you have learned.

What I Know	What I Would Like to Learn	What I Have Learned
a. ?	b. ?	c. ?
d. ?	e. ?	f. ?

As you observe day-to-day weather changes, you can see the powerful role of water in the air. Water vapor is the source of all condensation and **precipitation,** which is any form of water that falls from a cloud. Look at Figure 1. Clouds and fog, as well as rain, snow, sleet, and hail, are examples of some of the more noticeable weather conditions. **When it comes to understanding atmospheric processes, water vapor is the most important gas in the atmosphere.** Water vapor makes up only a small fraction of the gases in the atmosphere, varying from nearly 0 to about 4 percent by volume. But the importance of water in the air greatly exceeds what these small percentages would indicate.

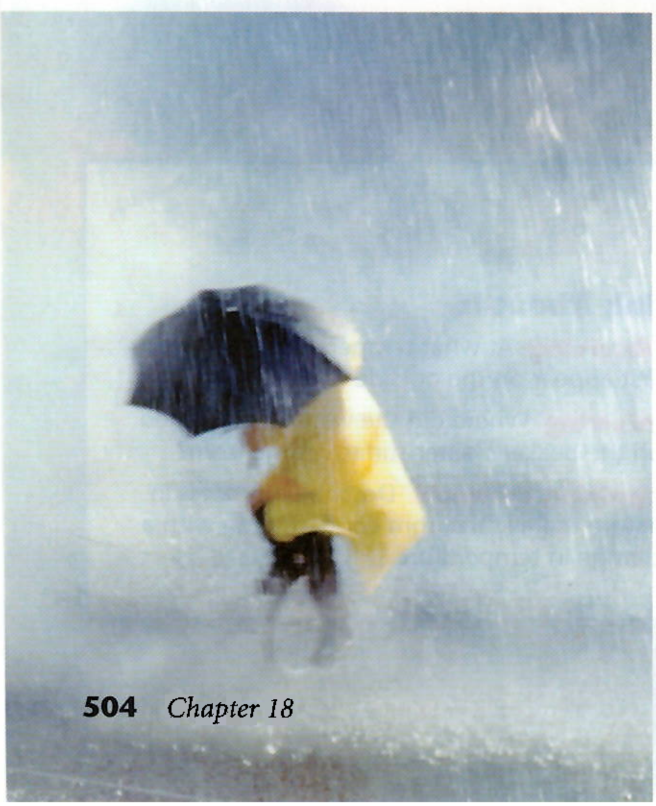


Figure 1 This downpour shows how precipitation can affect daily activities.

Water's Changes of State

The three states of matter are solid, liquid, and gas. Water can change from one state of matter to another—at temperatures and pressures experienced on Earth. This unique property allows water to freely leave the oceans as a gas and return again as a liquid, producing the water cycle. All water in the cycle must pass through the atmosphere as water vapor, even though the atmosphere only holds enough to make a global layer about 2 mm deep.

Reading Checkpoint *What is the range in volume percent of water in the atmosphere?*

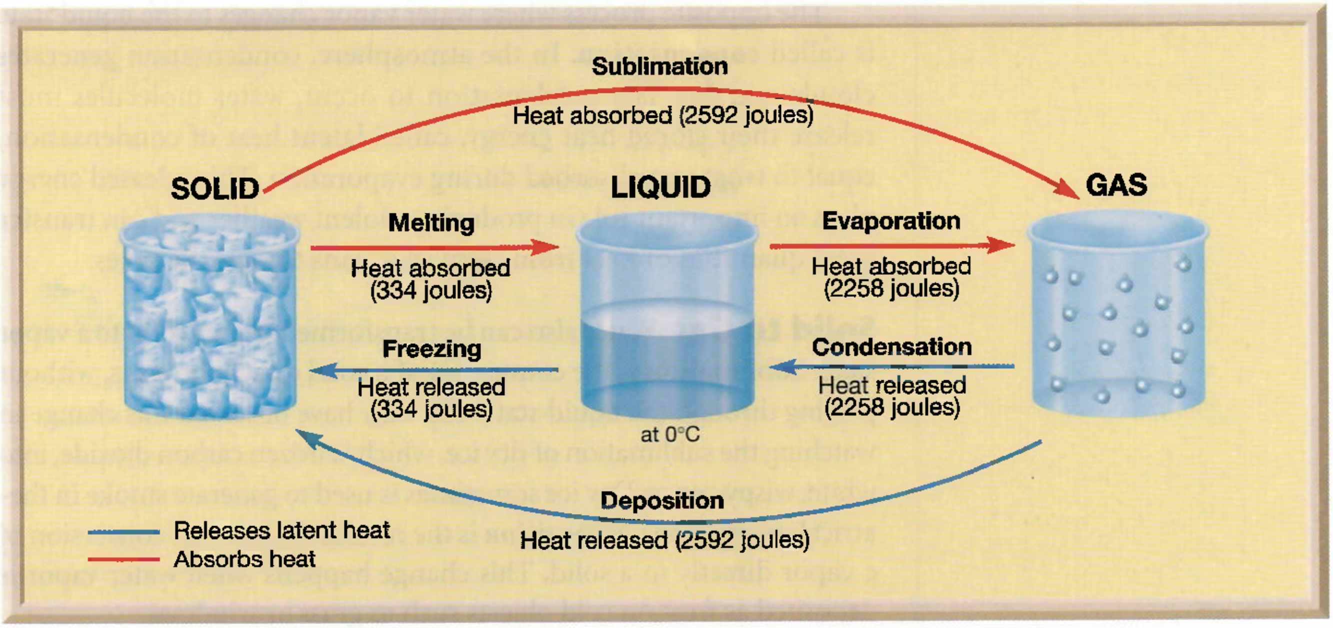


Figure 2 Changes of State The heat energy, in joules, is indicated for 1 gram of water.

Solid to Liquid

The process of changing state requires that energy is transferred in the form of heat. When heat is transferred to a glass of ice water, the temperature of the ice water remains a constant 0°C until all the ice has melted. If adding heat does not raise the temperature, then where does this energy go? In this case, the added heat breaks apart the crystal structure of the ice cubes. The bonds between water molecules in the ice crystals are broken forming the noncrystalline substance liquid water. You know this process as melting.

The heat used to melt ice does not produce a temperature change, so it is referred to as **latent heat.** *Latent* means "hidden," like the latent fingerprints hidden at a crime scene. This energy, measured in joules or calories, becomes stored in the liquid water and is not released as heat until the liquid returns to the solid state.

Latent heat plays a crucial role in many atmospheric processes. For example, the release of latent heat aids in forming the towering clouds often seen on warm summer days. It is the major source of energy for thunderstorms, tornadoes, and hurricanes.

Liquid to Gas

The process of changing a liquid to a gas is called **evaporation.** You see in Figure 2 that it takes approximately 2258 joules of energy to convert 1 gram of liquid water to water vapor. The energy absorbed by the water molecules during evaporation gives them the motion needed to escape the surface of the liquid and become a gas. This energy is referred to as latent heat of vaporization.

You might have experienced a cooling effect when stepping dripping wet from a swimming pool or bathtub. This cooling results because it takes considerable energy to evaporate water. In this situation, the energy comes from your skin—hence the expression that "evaporation is a cooling process."

The opposite process where water vapor changes to the liquid state is called **condensation.** In the atmosphere, condensation generates clouds and fog. For condensation to occur, water molecules must release their stored heat energy, called latent heat of condensation, equal to what was absorbed during evaporation. This released energy plays an important role in producing violent weather and can transfer great quantities of heat from tropical oceans toward the poles.

Solid to Gas Water also can be transformed from a solid to a vapor state. **Sublimation** is the conversion of a solid directly to a gas, without passing through the liquid state. You may have observed this change in watching the sublimation of dry ice, which is frozen carbon dioxide, into white, wispy vapor. Dry ice sometimes is used to generate smoke in theatrical productions. **Deposition** is the reverse process, the conversion of a vapor directly to a solid. This change happens when water vapor is deposited as frost on cold objects such as grass or windows.

Humidity

The general term for the amount of water vapor in air is **humidity.** Meteorologists use several methods to express the water-vapor content of the air. These include relative humidity and dew-point temperature.

Table 1 Water Vapor Needed for Saturation

Temperature		Water Vapor Content at Saturation (g/kg)
°C	(°F)	
−40	(−40)	0.1
−30	(−22)	0.3
−20	(−4)	0.75
−10	(14)	2
0	(32)	3.5
5	(41)	5
10	(50)	7
15	(59)	10
20	(68)	14
25	(77)	20
30	(86)	26.5
35	(95)	35
40	(104)	47

Saturation Imagine a closed jar half full of water and half full of dry air. As the water begins to evaporate from the water surface, a small increase in pressure can be detected in the air above. This increase is the result of the motion of the water-vapor molecules that were added to the air through evaporation. As more and more molecules escape from the water surface, the pressure in the air above increases steadily. This forces more and more water molecules to return to the liquid. Eventually, the number of vapor molecules returning to the surface will balance the number leaving. At that point, the air is said to be **saturated.** The amount of water vapor required for saturation depends on temperature as shown in Table 1. **When saturated, warm air contains more water vapor than saturated cold air.**

Relative Humidity The most familiar and most misunderstood term used to describe the moisture content of air is relative humidity. **Relative humidity is a ratio of the air's actual water-vapor content compared with the amount of water vapor air can hold at that temperature and pressure.** Relative humidity indicates how near the air is to saturation, rather than the actual quantity of water vapor in the air.

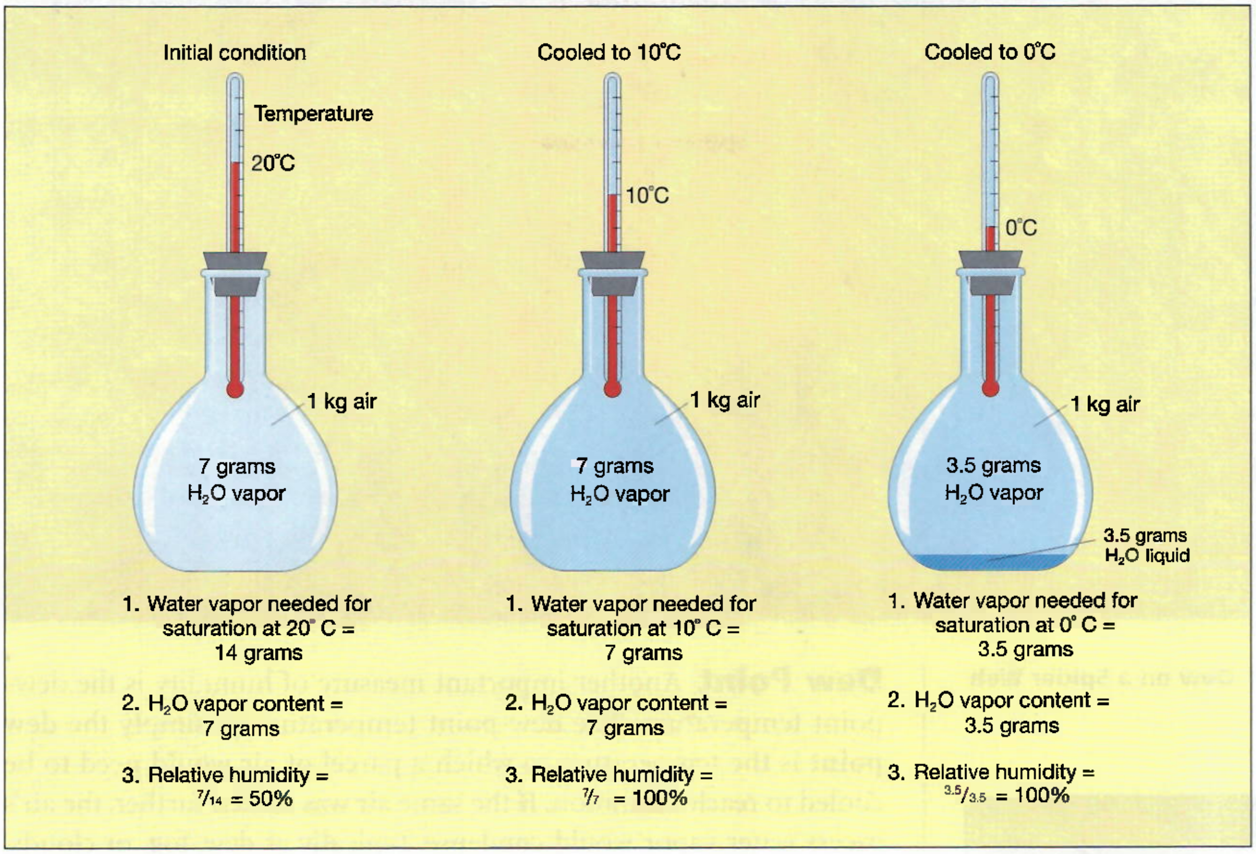


Figure 3 Relative humidity varies with temperature.

Relative humidity can be changed in two ways. First, it can be changed by adding or removing water vapor. In nature, moisture is added to air mainly by evaporation from the oceans and smaller bodies of water.

Second, because the amount of moisture needed for saturation depends on temperature, relative humidity varies with temperature. Notice in Figure 3 that when the flask is cooled from 20°C to 10°C, the relative humidity increases from 50 to 100 percent. However, once the air is saturated, further cooling does not change the relative humidity. Further cooling causes condensation, which keeps the air at its saturation level for the temperature. When air far above Earth's surface is cooled below its saturation level, some of the water vapor condenses to form clouds. Because clouds are made of liquid droplets, this moisture is no longer part of the water-vapor content of the air. **To summarize, when the water-vapor content of air remains constant, lowering air temperature causes an increase in relative humidity, and raising air temperature causes a decrease in relative humidity.**

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Figure 4 Dew on a Spider Web

Figure 5 Sling Psychrometer This psychrometer is used to measure both relative humidity and dew point.

Interpreting Photographs ***Identify the wet bulb and the dry bulb in this photograph.***

Dew Point Another important measure of humidity is the dew-point temperature. The dew-point temperature or simply the **dew point** is the temperature to which a parcel of air would need to be cooled to reach saturation. If the same air was cooled further, the air's excess water vapor would condense, typically as dew, fog, or clouds. During evening hours, objects near the ground often cool below the dew-point temperature and become coated with water. This is known as dew, shown on the spider web in Figure 4.

For every 10°C increase in temperature, the amount of water vapor needed for saturation doubles. Therefore, relatively cold saturated air at 0°C contains about half the water vapor of saturated air at a temperature of 10°C, and roughly one-fourth that of hot saturated air with a temperature of 20°C as shown in Table 1 on page 506. Because the dew point is the temperature at which saturation occurs, high dew-point temperatures indicate moist air, and low dew-point temperatures indicate dry air.

Measuring Humidity Relative humidity is commonly measured by using a **hygrometer.** One type of hygrometer, called a psychrometer, consists of two identical thermometers mounted side by side. See Figure 5. One thermometer, the dry-bulb thermometer, gives the present air temperature. The other, called the wet-bulb thermometer, has a thin cloth wick tied around the end.

To use the psychrometer, the cloth wick is saturated with water and air is continuously passed over the wick. This is done either by swinging the instrument freely in the air or by fanning air past it. Water evaporates from the wick, and the heat absorbed by the evaporating water makes the temperature of the wet bulb drop. The loss of heat that was required to evaporate water from the wet bulb lowers the thermometer reading. This temperature is referred to as the wet-bulb temperature.

The amount of cooling that takes place is directly proportional to the dryness of the air. The drier the air, the more moisture evaporates, and the lower is the temperature of the wet bulb. The larger the difference is between temperatures observed on the thermometers, the lower the relative humidity. If the air is saturated, no evaporation will occur, and the two thermometers will have identical readings. To determine the precise relative humidity and to calculate the dew point, standard tables are used.

A sling psychrometer would not be all that useful in a weather balloon used to monitor conditions in the upper atmosphere. A different type of hygrometer is used in instrument packages that transmit data back to a station on the ground. The electric hygrometer contains an electrical conductor coated with a chemical that absorbs moisture. The passage of current varies with the amount of moisture absorbed.

Q & A

Q *Why is the air in buildings so dry in the winter?*

A If the water-vapor content of air stays constant, an increase in temperature lowers the relative humidity, and a drop in temperature raises the relative humidity. During winter months, outside air is comparatively cold. When this air is drawn into a building, it is heated to room temperature. This causes the relative humidity to drop, often to uncomfortably low levels of 10 percent or lower. Living with dry air can mean static electrical shocks, dry skin, sinus headaches, or even nosebleeds.

Section 18.1 Assessment

Reviewing Concepts

1. What is the most important gas for understanding atmospheric processes?
2. What happens to heat during a change of state?
3. How does the temperature of air influence its ability to hold water?
4. What does relative humidity describe about air?
5. List two ways that relative humidity can be changed.
6. What does a low dew point indicate about the moisture content of air?

Critical Thinking

7. **Interpreting Illustrations** Study Figure 2. For 1 gram of water, how do the energy requirements for melting and evaporation compare?

Math Practice

8. The air over Fort Myers, Florida, has a dew point of 25°C. Fort Myers has twice the water vapor content of the air over St. Louis, Missouri, and four times the water vapor content as air over Tucson, Arizona. Determine the dew points for St. Louis and Tucson.

18.2 Cloud Formation

Reading Focus

Key Concepts

- What happens to air when it is compressed or allowed to expand?
- List four mechanisms that can cause air to rise.
- Contrast movements of stable and unstable air.
- What conditions in air favor condensation of water?

Vocabulary

- dry adiabatic rate
- wet adiabatic rate
- orographic lifting
- front
- temperature inversion
- condensation nuclei

Reading Strategy

Identifying Main Ideas Copy the table. As you read, write the main idea for each topic.

Topic	Main Idea
Adiabatic temperature changes	a. ____?____
Stability measurements	b. ____?____
Degrees of stability	c. ____?____

Figure 6 Clouds form when air is cooled to its dew point.

Recall that condensation occurs when water vapor changes to a liquid. Condensation may form dew, fog, or clouds. Although these three forms are different, all require saturated air to develop. Saturation occurs either when enough water vapor is added to air or, more commonly, when air is cooled to its dew point.

Near Earth's surface, heat is quickly exchanged between the ground and the air above. During evening hours, the surface radiates heat away, causing the surface and adjacent air to cool rapidly. This radiational cooling causes the formation of dew and some types of fog. In contrast, clouds, like those shown in Figure 6, often form during the warmest part of the day. Clearly, some other process must cool air enough to generate clouds.

Air Compression and Expansion

If you have pumped up a bicycle tire, you might have noticed that the pump barrel became warm. The increase in temperature you felt resulted from the work you did on the air to compress it. When air is compressed, the motion of gas molecules increases and the air temperature rises. The opposite happens when air is allowed to escape from a bicycle tire. The air expands and cools. The expanding air pushes on the surrounding air and cools by an amount equal to the energy used up.

Adiabatic Temperature Changes Temperature changes that happen even though heat isn't added or subtracted are called *adiabatic temperature changes.* They result when air is compressed or allowed to expand. **When air is allowed to expand, it cools, and when it is compressed, it warms.**

Expansion and Cooling As you travel from Earth's surface upward through the atmosphere, the atmospheric pressure decreases. This happens because there are fewer and fewer gas molecules. Any time a volume of air moves upward, it passes through regions of successively lower pressure. As a result, the ascending air expands and cools. Unsaturated air cools at the constant rate of 10°C for every 1000 meters of ascent. In contrast, descending air encounters higher pressures, compresses, and is heated 10°C for every 1000 meters it moves downward. This rate of cooling or heating applies only to unsaturated air and is called the **dry adiabatic rate.**

If a parcel of air rises high enough, it will eventually cool to its dew point. Here the process of condensation begins. From this point on as the air rises, latent heat of condensation stored in the water vapor will be released. Although the air will continue to cool after condensation begins, the released latent heat works against the adiabatic cooling process. This slower rate of cooling caused by the addition of latent heat is called the **wet adiabatic rate.** Because the amount of latent heat released depends on the quantity of moisture present in the air, the wet adiabatic rate varies from 5–9°C per 1000 meters.

Figure 7 shows the role of adiabatic cooling in the formation of clouds. Note that from the surface up to the condensation level the air cools at the dry adiabatic rate. The wet adiabatic rate begins at the condensation level.

Reading Checkpoint ***What happens to heat stored in water vapor when it is cooled to its dew point?***

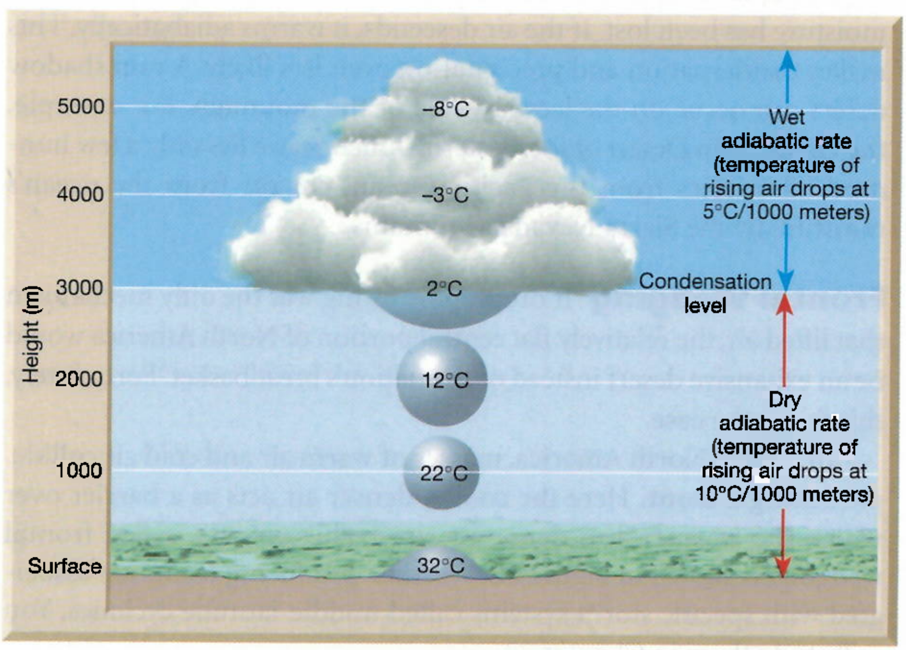


Figure 7 Cloud Formation by Adiabatic Cooling Rising air cools at the dry adiabatic rate of 10°C per 1000 meters, until the air reaches the dew point and condensation (cloud formation) begins. As air continues to rise, the latent heat released by condensation reduces the rate of cooling.
Interpreting Diagrams ***Use this diagram to determine the approximate air temperature at 3500 m.***

Processes that Lift Air

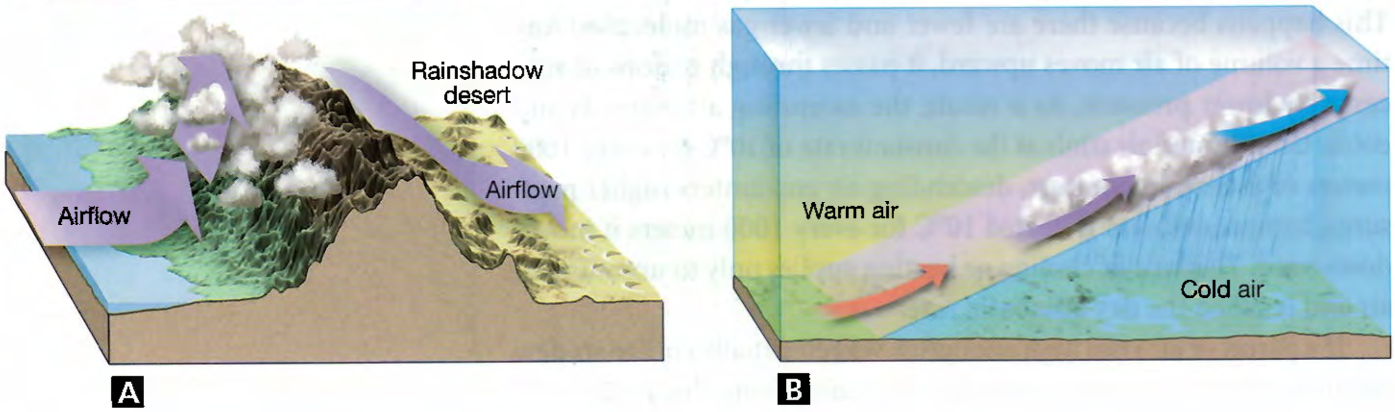


Figure 8 A Orographic Lifting B Frontal Wedging
Relating Cause and Effect ***Why does the warm air mass move upward over the cold air mass?***

Processes That Lift Air

In general, air resists vertical movement. Air located near the surface tends to stay near the surface. Air far above the surface tends to remain far above the surface. Some exceptions to this happen when conditions in the atmosphere make air buoyant enough to rise without the aid of outside forces. In other situations, clouds form because there is some mechanical process that forces air to rise. **Four mechanisms that can cause air to rise are orographic lifting, frontal wedging, convergence, and localized convective lifting.**

Orographic Lifting When elevated terrains, such as mountains, act as barriers to air flow, **orographic lifting** of air occurs. Look at Figure 8A. As air goes up a mountain slope, adiabatic cooling often generates clouds and precipitation. Many of the rainiest places on Earth are located on these windward mountain slopes.

By the time air reaches the leeward side of a mountain, much of its moisture has been lost. If the air descends, it warms adiabatically. This makes condensation and precipitation even less likely. A rain shadow desert can occur on the leeward side of the mountain. For example, the Great Basin Desert of the western United States lies only a few hundred kilometers from the Pacific Ocean, cut off from the ocean's moisture by the Sierra Nevada Mountains.

Frontal Wedging If orographic lifting was the only mechanism that lifted air, the relatively flat central portion of North America would be an expansive desert instead of the nation's breadbasket. Fortunately, this is not the case.

In central North America, masses of warm air and cold air collide, producing a **front.** Here the cooler, denser air acts as a barrier over which the warmer, less dense air rises. This process, called frontal wedging, is shown in Figure 8B. Weather-producing fronts are associated with specific storm systems called middle-latitude cyclones. You will study these in Chapter 20.

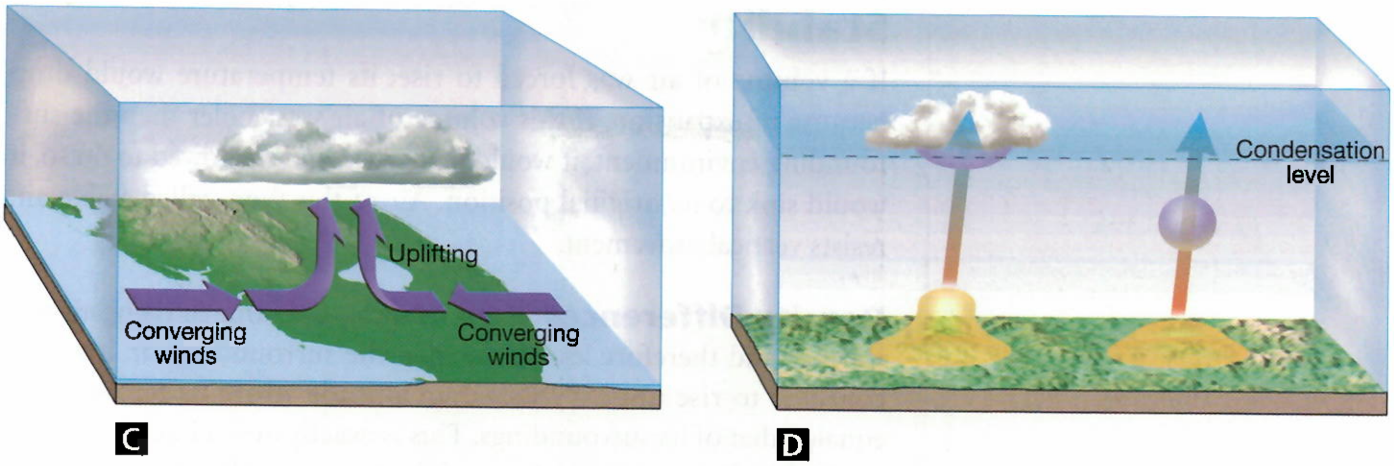


Figure 8 C Convergence
D Localized Convective Lifting

Convergence Recall that the collision of contrasting air masses forces air to rise. In a more general sense, whenever air in the lower atmosphere flows together, lifting results. This is called convergence. When air flows in from more than one direction, it must go somewhere. Because it cannot go down, it goes up, as shown in Figure 8C. This leads to adiabatic cooling and possibly cloud formation.

The Florida peninsula provides an example of how convergence can cause cloud development and precipitation. On warm days, the airflow is from the ocean to the land along both coasts of Florida. This leads to a pileup of air along the coasts and general convergence over the peninsula. This pattern of air movement and the uplift that results is helped along by intense solar heating of the land. The result is that the peninsula of Florida experiences the greatest number of mid-afternoon thunderstorms in the United States.

Localized Convective Lifting On warm summer days, unequal heating of Earth's surface may cause pockets of air to be warmed more than the surrounding air. For example, air above a paved parking lot will be warmed more than the air above an adjacent wooded park. Consequently, the parcel of air above the parking lot, which is warmer and less dense than the surrounding air, will move upward, as shown in Figure 8D. These rising parcels of warmer air are called thermals. The process that produces rising thermals is localized convective lifting. Birds such as hawks and eagles use these thermals to carry them to great heights where they can gaze down on unsuspecting prey. People have learned to use these warm parcels effectively for hang gliding. When warm parcels of air rise above the condensation level, clouds form. These clouds may produce mid-afternoon rain showers.

Reading Checkpoint ***What are thermals?***

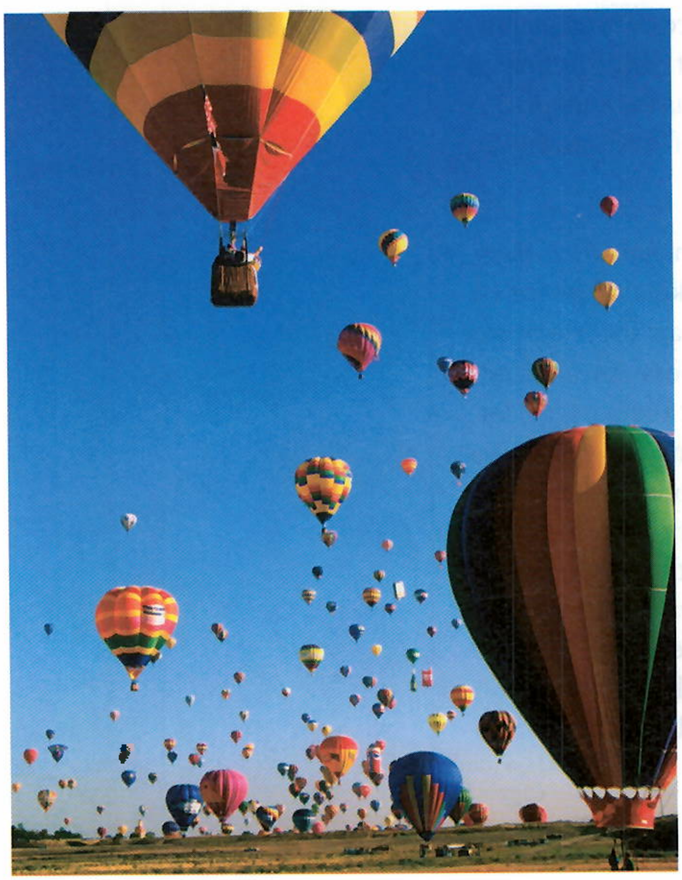
Stability

If a volume of air was forced to rise, its temperature would drop because of expansion. If this volume of air was cooler than the surrounding environment, it would be denser, and if allowed to do so, it would sink to its original position. Air of this type, called stable air, resists vertical movement.

Density Differences If this imaginary volume of rising air was warmer and therefore less dense than the surrounding air, it would continue to rise until it reached an altitude where its temperature equaled that of its surroundings. This is exactly how a hot-air balloon works. The balloon rises as long as it is warmer and less dense than the surrounding air, as shown in Figure 9. This type of air is classified as unstable air. **Stable air tends to remain in its original position, while unstable air tends to rise.**

Stability Measurements Air stability is determined by measuring the temperature of the atmosphere at various heights. The rate of change of air temperature with height is called the environmental lapse rate. This rate is determined from observations made by aircraft and by radiosondes. A radiosonde is an instrument designed to collect weather data high in the atmosphere. Radiosondes are often carried into the air by balloons. It is important not to confuse the environmental lapse rate with adiabatic temperature changes.

Figure 9 Hot-air balloons will rise as long as the air inside them is warmer than the air in the atmosphere surrounding them.



Degrees of Stability Air is stable when the temperature decreases gradually with increasing altitude. The most stable conditions happen when air temperature actually increases with height, called a **temperature inversion.** Temperature inversions frequently happen on clear nights as a result of radiation cooling off Earth's surface. The inversion is created because the ground and the air immediately above the ground will cool more rapidly than air higher above the ground. Under these conditions, there is very little vertical air movement. In contrast, air is considered unstable when the air close to the surface of Earth is significantly warmer than the air higher above the surface, indicating a large environmental lapse rate. Under these conditions, the air actually turns over, as the warm air below rises and is displaced by the colder air higher above the ground.

Figure 10 These clouds provide evidence of unstable conditions in the atmosphere.

Stability and Daily Weather Recall that stable air resists vertical movement and that unstable air rises freely. But how do these facts apply to the daily weather?

Because stable air resists upward movement, you might conclude that clouds won't form when stable conditions are present in the atmosphere. Although this seems reasonable, remember that there are processes that force air above Earth's surface. These include orographic lifting, frontal wedging, and convergence. When stable air is forced above Earth's surface, the clouds that form are widespread and have little vertical thickness when compared to their horizontal dimension. Precipitation, if any, is light to moderate.

In contrast, clouds associated with the lifting of unstable air are towering and often generate thunderstorms and occasionally even a tornado. For this reason, on a dreary, overcast day with light drizzle, stable air has been forced above Earth's surface. During a day when cauliflower-shaped clouds appear to be growing as if bubbles of hot air are surging upward, the air moving up is unstable. Figure 10 shows cauliflower-shaped clouds caused by the rising of unstable air.

Reading Checkpoint ***What types of weather can result when stable air rises?***

Condensation

Recall that condensation happens when water vapor in the air changes to a liquid. This may be in the form of dew, fog, or clouds. **For any of these forms of condensation to occur, the air must be saturated.** Saturation occurs most commonly when air is cooled to its dew point, or less often when water vapor is added to the air.

Types of Surfaces Generally, there must be a surface for water vapor to condense on. When dew forms, objects at or near the ground, such as grass and car windows, serve this purpose. But when condensation occurs in the air above the ground, tiny bits of particulate matter, called **condensation nuclei,** serve as surfaces for water-vapor condensation. These nuclei are important because if they are absent, a relative humidity much above 100 percent is needed to produce clouds.

Condensation nuclei such as microscopic dust, smoke, and salt particles from the ocean are abundant in the lower atmosphere. Because of these plentiful particles, relative humidity rarely exceeds 100 percent. Some particles, such as ocean salt, are especially good nuclei because they absorb water. When condensation takes place, the initial growth rate of cloud droplets is rapid. It diminishes quickly because the excess water vapor is quickly absorbed by the numerous competing particles. This results in the formation of a cloud consisting of millions upon millions of tiny water droplets. These droplets are all so fine that they remain suspended in air. In the next section, you will examine types of clouds and the precipitation that forms from them.

Section 18.2 Assessment

Reviewing Concepts

1. Describe what happens to air temperature when work is done on the air to compress it.
2. What does stability mean in terms of air movement?
3. List four mechanisms that cause air to rise.
4. Describe conditions that cause condensation of liquid water in air.
5. What is a temperature inversion?
6. Which types of condensation nuclei are especially good for condensation to form?

Critical Thinking

7. **Hypothesizing** Study a world map. Hypothesize about other regions on Earth, other than the Florida peninsula, where convergence might cause cloud development and precipitation.

Connecting Concepts

Air Temperature Review the description of atmospheric temperature changes in Section 17.1. Then write a paragraph explaining how these differ from adiabatic temperature changes in parcels of air.

18.3 Cloud Types and Precipitation

Reading Focus

Key Concepts

- How are clouds classified?
- How are clouds and fogs similar and different?
- What must happen in order for precipitation to form?
- What controls the type of precipitation that reaches Earth's surface?

Vocabulary

- cirrus
- cumulus
- stratus
- Bergeron process
- supercooled water
- supersaturated air
- collision-coalescence process

Reading Strategy

Building Vocabulary Copy the table. As you read, add definitions.

Vocabulary Term	Definition
Cirrus	a. ___?___
Cumulus	b. ___?___
Stratus	c. ___?___
Coalescence	d. ___?___

Clouds are among the most striking and noticeable effects of the atmosphere and its weather. Clouds are a form of condensation best described as visible mixtures of tiny droplets of water or tiny crystals of ice. Clouds are of interest to meteorologists because clouds show what is going on in the atmosphere. If you try to recognize different types of clouds, you might find it hard to do. But, if you learn the basic classification scheme for clouds, recognizing cloud types will be easy.

Figure 11 Cirrus Clouds

Types of Clouds

Clouds are classified on the basis of their form and height. The three basic forms are: cirrus, cumulus, and stratus. All other clouds reflect one of these three basic forms or are combinations or modifications of them.

Cirrus (*cirrus* = a curl of hair) clouds are high, white, and thin. They can occur as patches or as delicate veil-like sheets or extended wispy fibers that often have a feathery appearance. An example of cirrus clouds is shown in Figure 11.

Cumulus (*cumulus* = a pile) clouds consist of rounded individual cloud masses. Refer to Figure 10 on page 515. Normally, they have a flat base and the appearance of rising domes or towers. These clouds are frequently described as having a cauliflower structure.

Stratus (*stratum* = a layer) clouds are best described as sheets or layers that cover much or all of the sky. While there may be minor breaks, there are no distinct individual cloud units.

There are three levels of cloud heights: high, middle, and low, as shown in Figure 12. High clouds normally have bases above 6000 meters. Middle clouds generally occupy heights from 2000 to 6000 meters. Low clouds form below 2000 meters. The altitudes listed for each height category are not hard and fast. There is some seasonal and latitudinal variation. For example, at high latitudes or during cold winter months in the mid-latitudes, high clouds often are found at lower altitudes.

High Clouds Three cloud types make up the family of high clouds: cirrus, cirrostratus, and cirrocumulus. Look at Figure 12. Cirrocumulus clouds consist of fluffy masses, while cirrostratus clouds are flat layers. All high clouds are thin and white and are often made up of ice crystals. This is because of the low temperatures and small quantities of water vapor present at high altitudes. These clouds are not considered precipitation makers. However, when cirrus clouds are followed by cirrocumulus or cirrostratus clouds and increased sky coverage, they may warn of approaching stormy weather.

Middle Clouds Clouds that appear in the middle range, from about 2000 to 6000 meters, have the prefix *alto-* as part of their name. Altocumulus clouds are composed of rounded masses that differ from

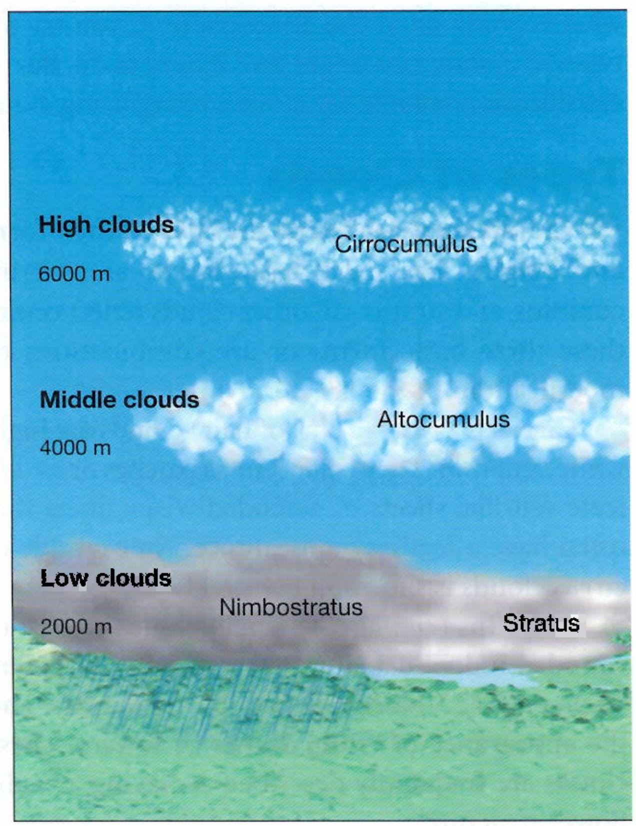


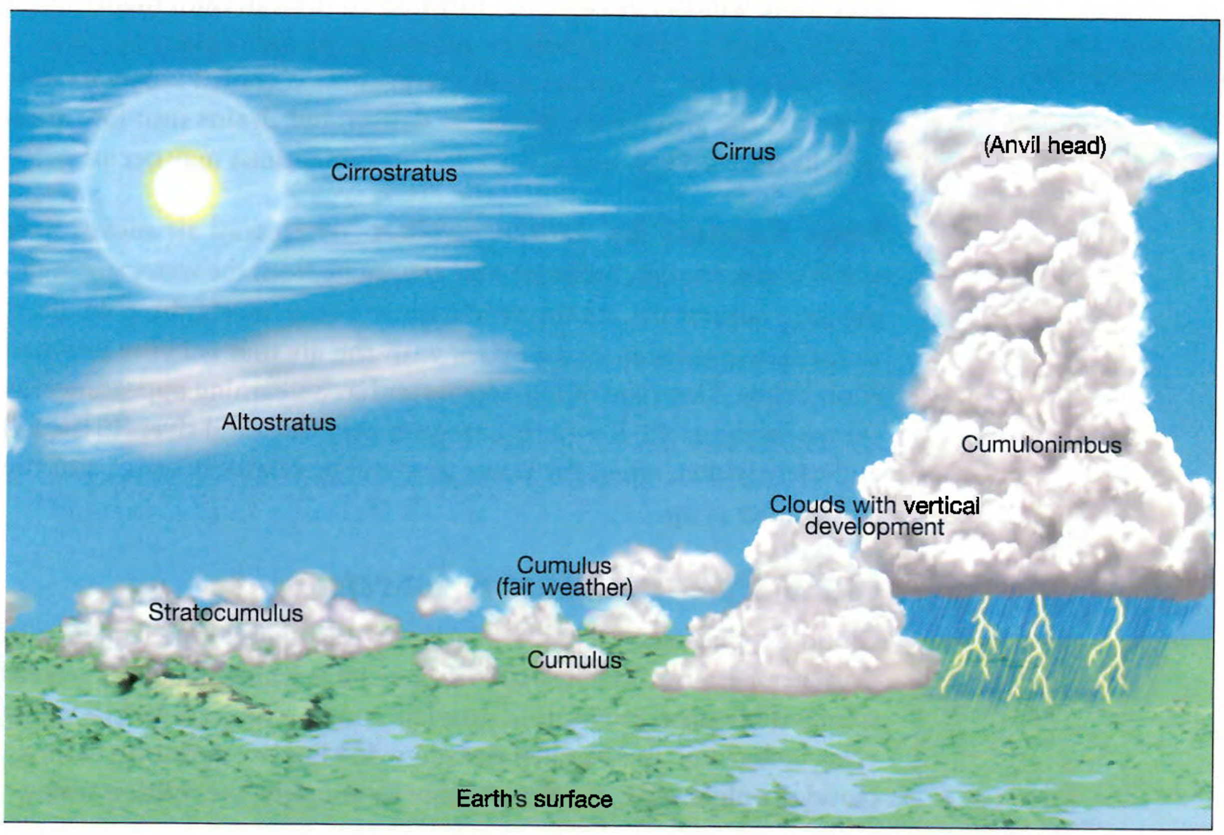
Figure 12 Cloud Classification Clouds are classified according to form and height.
Interpreting Diagrams ***Which cloud types are the chief precipitation makers?***

cirrocumulus clouds in that altocumulus clouds are larger and denser, as shown in Figure 12. Altostratus clouds create a uniform white to grayish sheet covering the sky with the sun or moon visible as a bright spot. Infrequent light snow or drizzle may accompany these clouds.

Low Clouds There are three members in the family of low clouds: stratus, stratocumulus, and nimbostratus. As illustrated in Figure 12, stratus clouds are a uniform, fog-like layer of clouds that frequently covers much of the sky. Occasionally, these clouds may produce light precipitation. When stratus clouds develop a scalloped bottom that appears as long parallel rolls or broken rounded patches, they are called stratocumulus clouds.

Nimbostratus clouds derive their name from the Latin word *nimbus*, which means "rainy cloud," and *stratus*, which means "to cover with a layer." As the name suggests, nimbostratus clouds are one of the main precipitation makers. Nimbostratus clouds form during stable conditions. You might not expect clouds to develop in stable air. But cloud growth of this type is common when air is forced upward, as occurs along a mountain range, a front, or where converging winds cause air to rise. Such a forced upward movement of stable air can result in a cloud layer that is largely horizontal compared to its depth.

Reading Checkpoint ***What does the Latin word* stratus *mean?***



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Clouds of Vertical Development Some clouds do not fit into any one of the three height categories mentioned. Such clouds have their bases in the low height range but often extend upward into the middle or high altitudes. They all are related to one another and are associated with unstable air. Although cumulus clouds are often connected with fair weather, they may grow dramatically under the proper circumstances. Once upward movement is triggered, acceleration is powerful, and clouds with great vertical range form. The end result often is a cumulonimbus cloud that may produce rain showers or a thunderstorm.

Fog

Physically, there is no difference between a fog and a cloud. Their appearance and structure are the same. The difference is the method and place of formation. Clouds result when air rises and cools adiabatically. Most fogs are the result of radiation cooling or the movement of air over a cold surface. Fogs also can form when enough water vapor is added to the air to bring about saturation. **Fog is defined as a cloud with its base at or very near the ground.** When fog is dense, visibility may be only a few dozen meters or less, making travel not only difficult but often dangerous.

Figure 13 This steam fog rose from upper St. Regis Lake, Adirondack Mountains, New York.

Fogs Caused by Cooling A blanket of fog is produced in some West Coast locations when warm, moist air from the Pacific Ocean moves over the cold California Current and then is carried onshore by prevailing winds. Fogs also can form on cool, clear, calm nights when Earth's surface cools rapidly by radiation. As the night progresses, a thin layer of air in contact with the ground is cooled below its dew point. As the air cools, it becomes denser and drains into low areas such as river valleys, where thick fog accumulations may occur.

Fogs Caused by Evaporation When cool air moves over warm water, enough moisture may evaporate from the water surface to produce saturation. As the rising water vapor meets the cold air, it immediately condenses and rises with the air that is being warmed from below. This type of fog over water has a steaming appearance, as shown in Figure 13. It is fairly common over lakes and rivers in the fall and early winter, when the water may still be relatively warm and the air is rather crisp.

How Precipitation Forms

Cloud droplets are very tiny, averaging less than 20 micrometers in diameter. Because of their small size, the rate at which cloud droplets fall is incredibly slow. Most cloud droplets would evaporate before falling a few meters into unsaturated air below. **For precipitation to form, cloud droplets must grow in volume by roughly one million times.**

Cold Cloud Precipitation

The **Bergeron process,** shown in Figure 14, relies on two physical processes: supercooling and supersaturation. Cloud droplets do not freeze at 0°C as expected. In fact, pure water suspended in air does not freeze until it reaches a temperature of nearly −40°C. Water in the liquid state below 0°C is said to be **supercooled.** Supercooled water will readily freeze if it impacts a solid object. Freezing nuclei are materials that have a crystal form that closely matches that of ice. Freezing nuclei can cause supercooled water to freeze.

When air is saturated (100% relative humidity) with respect to water, it is **supersaturated** with respect to ice (greater than 100% humidity). Ice crystals cannot coexist with water droplets in the air because the air "appears" supersaturated to the ice crystals. Any excess water vapor becomes ice that lowers the relative humidity near the surrounding droplets. Water droplets then evaporate to provide a continual source of water vapor for the growth of ice crystals.

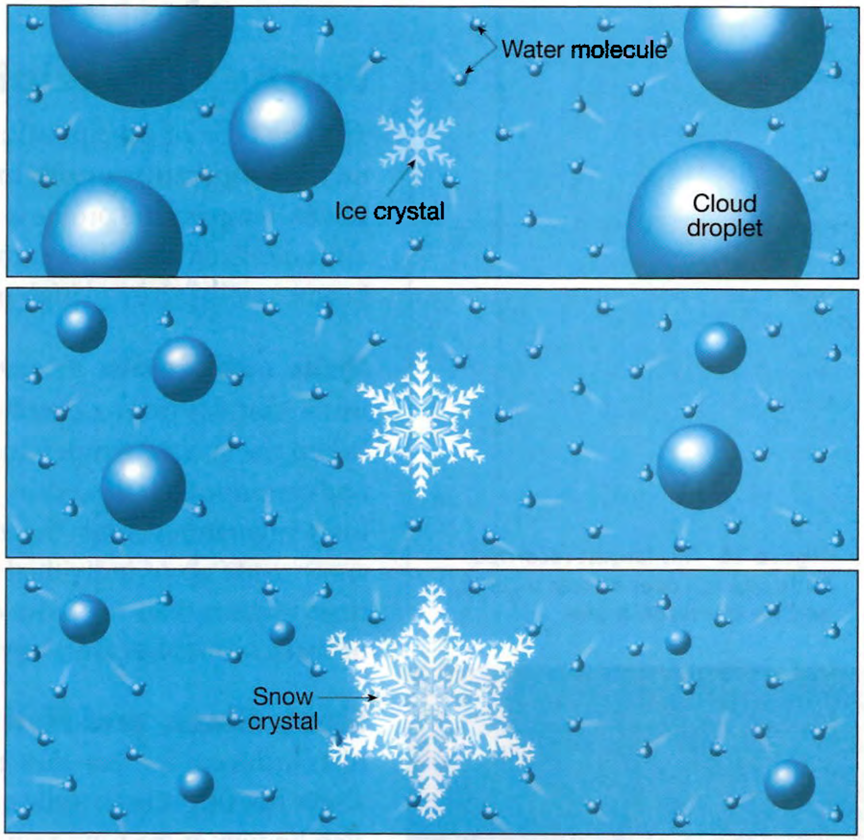

Figure 14 The Bergeron Process Ice crystals grow at the expense of cloud droplets until they are large enough to fall. The size of these particles has been greatly exaggerated.

Because the level of supersaturation with respect to ice can be quite high, the growth of ice crystals is rapid enough to produce crystals that are large enough to fall. As they fall the ice crystals contact cloud drops causing them to freeze. A chain reaction can occur and large crystals, called snowflakes form. When the surface temperature is above 4°C, snowflakes usually melt before they reach the ground. Even on a hot summer day, a heavy downpour may have started as a snowstorm high in the clouds.

Warm Cloud Precipitation Much rainfall can be associated with clouds located well below the freezing level, especially in the tropics. In warm clouds, the mechanism that forms raindrops is the **collision-coalescence process.** Some water-absorbing particles, such as salt, can remove water vapor from the air at relative humidities less than 100 percent, forming drops that are quite large. As these large droplets move through the cloud, they collide and coalesce (join together) with smaller, slower droplets.

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Forms of Precipitation

The type of precipitation that reaches Earth's surface depends on the temperature profile in the lowest few kilometers of the atmosphere. Temperature profile is the way the air temperature changes with altitude. Even on a hot summer day, a heavy downpour may have begun as a snowstorm high in the clouds overhead.

Rain and Snow In meteorology, the term *rain* means drops of water that fall from a cloud and have a diameter of at least 0.5 mm. When the surface temperature is above 4°C, snowflakes usually melt and continue their descent as rain before they reach the ground. At very low temperatures (when the moisture content of air is small) light, fluffy snow made up of individual six-sided ice crystals forms. At temperatures warmer than −5°C, ice crystals join into larger clumps. Snowfalls of these snowflakes are heavy and have high moisture contents.

Figure 15 This largest recorded hailstone fell over Kansas in 1970 and weighed 766 grams.

Sleet, Glaze, and Hail Sleet is the fall of small particles of clear-to-translucent ice. For sleet to form, a layer of air with temperatures above freezing must overlie a subfreezing layer near the ground. Glaze, also known as freezing rain, results when raindrops become supercooled (below 0°C) as they fall through subfreezing air near the ground and turn to ice when they impact objects.

Hail is produced in cumulonimbus clouds. Hailstones begin as small ice pellets that grow by collecting supercooled water droplets as they fall through a cloud. If the ice pellets encounter a strong updraft, they may be carried upward and begin the downward journey once more. Each trip through the supercooled portion of the cloud may be represented by another layer of ice, as shown in Figure 15.

Section 18.3 Assessment

Reviewing Concepts

1. How are clouds classified?
2. Compare and contrast clouds and fogs.
3. What must happen in order for precipitation to form?
4. Describe how the temperature profile of air near Earth's surface controls the type of precipitation that falls to the ground.

Critical Thinking

5. **Predicting** What type of precipitation would fall to Earth's surface if a thick layer of air near the ground was −8°C?
6. **Classifying** Identify the following cloud types as producers of heavy, light, or generally no precipitation.
   a. cirrocumulus b. cumulonimbus
   c. stratus d. nimbostratus

Writing in Science

Compare-Contrast Paragraph Write a paragraph comparing the Bergeron and collision-coalescence processes. Relate each to the type(s) of precipitation that can result.

people and the ENVIRONMENT

Atmospheric Stability and Air Pollution

Air quality is closely linked to the atmosphere's ability to scatter pollutants. Perhaps you've heard "Dilution is the solution to pollution." To a large degree, this is true. If the air into which pollution is released is not dispersed, the air will become more toxic. Two of the most important atmospheric conditions affecting the distribution of pollutants are wind strength and air stability.

When winds are weak or calm, the concentration of pollutants is higher than when winds are strong. High wind speeds mix polluted air into a larger volume of surrounding air, causing the pollution to be more diluted. When winds are light, there is less turbulence and mixing, so the concentration of pollutants is higher.

Atmospheric stability affects vertical movements of air. In general, the larger the extent of vertical mixing, the better the air quality is. During a temperature inversion, the atmosphere is very stable and it does not move much vertically. Warm air overlying cooler air acts as a lid and prevents upward movement, which leaves pollutants trapped near the ground, as shown in Figure 16.

Some inversions form near the ground, while others form higher above the ground. A surface inversion develops close to the ground on clear and relatively calm nights because the ground is a better radiator of heat than the air above it. Radiation from the ground to the clear night sky causes more rapid cooling at the surface than higher in the atmosphere. The result is that the air close to the ground is cooled more than the air above, yielding a temperature profile similar to the one shown in Figure 17. After sunrise, the ground is heated and the inversion disappears.

Although surface inversions usually are shallow, they may be thick in regions where the land surface is uneven. Because cold air is denser than warm air, the chilled air near the surface gradually drains from slopes into adjacent lowlands and valleys. As might be expected, these thicker surface inversions will not spread out as quickly after sunrise.

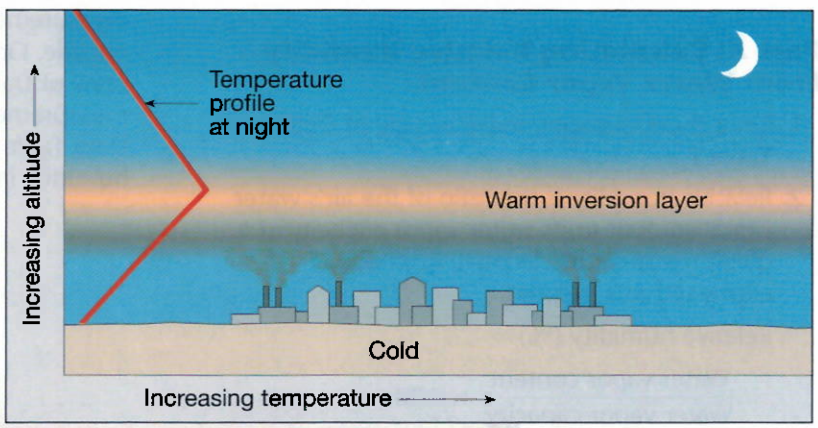


Figure 17 General Temperature Profile for a Surface Inversion

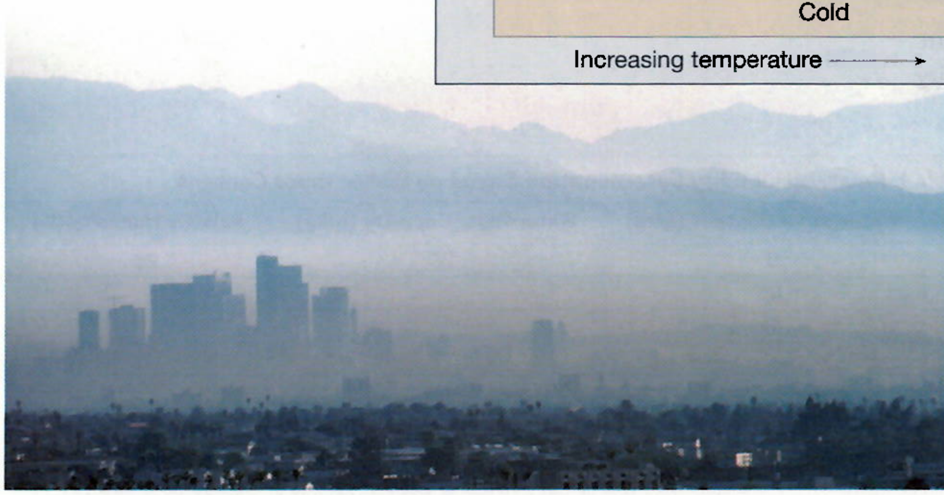


Figure 16 Air Pollution in Downtown Los Angeles Temperatures inversions act as lids to trap pollutants below.

Exploration Lab

Measuring Humidity

Relative humidity is a measurement used to describe water vapor in the air. In general, it expresses how close the air is to saturation. In this lab, you will use a psychrometer and a data table to determine the relative humidity of air.

Problem How can relative humidity be determined?

Materials

- calculator
- water at room temperature
- psychrometer

Alternative materials for psychrometer:

- 2 thermometers
- cotton gauze
- paper fan
- string

Skills Observing, Measuring, Analyzing Data, Calculating

Procedure

Part A: Calculating Relative Humidity From Water Vapor Content

1. On a sheet of paper, make a copy of Data Table 1.
2. Relative humidity is the ratio of the air's water vapor content to its water vapor capacity at a given temperature. Relative humidity is expressed as a percent.

   Relative humidity (%) =

   $$\frac{\text{Water vapor content}}{\text{Water vapor capacity}} \times 100$$

3. At 25°C, the water vapor capacity is 20 g/kg. Use this information to complete Data Table 1.

Part B: Determining Relative Humidity Using a Psychrometer

4. A psychrometer consists of two thermometers. The wet-bulb thermometer has a cloth wick that is wet with water and spun for about 1 minute. Relative humidity is determined by the difference in temperature reading between the dry-bulb temperature and the wet-bulb temperature, and using Data Table 2. For example, suppose a dry-bulb temperature is measured as 20°C, and a wet-bulb temperature is 14°C. Read the relative humidity from Data Table 2.
5. If a psychrometer is not available, construct a wet-bulb thermometer by tying a piece of cotton gauze around the end of a thermometer. Wet it with room-temperature water and fan it until the temperature stops changing.
6. Make wet-bulb and dry-bulb temperature measurements for air in your classroom and air outside. On a separate sheet of paper, make a copy of Data Table 3. Record your measurements. Use your measurements and Data Table 2 to determine the relative humidity inside and outside.

Data Table 1 Relative Humidity Determination Based on Water Vapor Content

Air Temperature (°C)	Water Vapor Content (g/kg)	Water Vapor Capacity (g/kg)	Relative Humidity (%)
25	5	20	25
25	12		
25	18		

Data Table 2 Relative Humidity (percent)

Dry-bulb Temperature (°C)	Depression of Wet-bulb Temperature (Dry-bulb Temperature – Wet-bulb Temperature = Depression of the Wet Bulb)																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
−20	28																					
−18	40																					
−16	48	0																				
−14	55	11																				
−12	61	23																				
−10	66	33	0																			
−8	71	41	13																			
−6	73	48	20	0																		
−4	77	54	43	11																		
−2	79	58	37	20	1																	
0	81	63	45	28	11																	
2	83	67	51	36	20	6																
4	85	70	56	42	27	14																
6	86	72	59	46	35	22	10	0														
8	87	74	62	51	39	28	17	6														
10	88	76	65	54	43	33	24	13	4													
12	88	78	67	57	48	38	28	19	10	2												
14	89	79	69	60	50	41	33	25	16	8	1											
16	90	80	71	62	54	45	37	29	21	14	7	1										
18	91	81	72	64	56	48	40	33	26	19	12	6	0									
20	91	82	74	66	58	51	44	36	30	23	17	11	5	0								
22	92	83	75	68	60	53	46	40	33	27	21	15	10	4	0							
24	92	84	76	69	62	55	49	42	36	30	25	20	14	9	4	0						
26	92	85	77	70	64	57	51	45	39	34	28	23	18	13	9	5						
28	93	86	78	71	65	59	53	47	42	36	31	26	21	17	12	8	2					
30	93	86	79	72	66	61	55	49	44	39	34	29	25	20	16	12	8	4				
32	93	86	80	73	68	62	56	51	46	41	36	32	27	22	19	14	11	8	4			
34	93	86	81	74	69	63	58	52	48	43	38	34	30	26	22	18	14	11	8	5		
36	94	87	81	75	69	64	59	54	50	44	40	36	32	28	24	21	17	13	10	7	4	
38	94	87	82	76	70	66	60	55	51	46	42	38	34	30	26	23	20	16	13	10	7	5
40	94	89	82	76	71	67	61	57	52	48	44	40	36	33	29	25	22	19	16	13	10	7

Relative Humidity Values

Data Table 3 Relative Humidity Determinations Using Dry- and Wet-Bulb Thermometers

	Inside	Outside
Dry-bulb temperature (°C)		
Wet-bulb temperature (°C)		
Difference between dry-bulb and wet-bulb temperatures (°C)		
Relative humidity (%)		

Analyze and Conclude

1. **Comparing and Contrasting** How do the relative humidity measurements for inside and outside compare? Why are your determinations similar or different?
2. **Applying Concepts** Explain the principle behind using a psychrometer to determine relative humidity.
3. **Applying Concepts** Suppose you hear on the radio that the relative humidity is 90 percent on a winter day. Can you conclude that this air contains more moisture than air on a summer day with a 40 percent relative humidity? Explain why or why not.
4. **Applying Concepts** Why is a cool basement often damp in the summer?

CHAPTER 18

Study Guide

18.1 Water in the Atmosphere

Key Concepts

- Water vapor is the most important gas in the atmosphere for understanding atmospheric processes.
- The process of changing state requires that energy is transferred in the form of heat.
- When saturated, warm air contains more water vapor than cold air.
- Relative humidity is a ratio of the air's actual water-vapor content compared with the amount of water vapor needed for saturation at that temperature and pressure.
- When the water-vapor content of air remains constant, lowering air temperature causes an increase in relative humidity, and raising air temperature causes a decrease in relative humidity.

Vocabulary

precipitation, *p. 504;* latent heat, *p. 505;* evaporation, *p. 505;* condensation, *p. 506;* sublimation, *p. 506;* deposition, *p. 506;* humidity, *p. 506;* saturated, *p. 506;* relative humidity, *p. 506;* dew point, *p. 508;* hygrometer, *p. 508*

18.2 Cloud Formation

Key Concepts

- When air is allowed to expand, it cools, and when it is compressed, it warms.
- Four mechanisms that can cause air to rise are orographic lifting, frontal wedging, convergence, and localized convective lifting.
- Stable air tends to remain in its original position, while unstable air tends to rise.
- For condensation of water to occur, the air must be saturated.

Vocabulary

dry adiabatic rate, *p. 511;* wet adiabatic rate, *p. 511;* orographic lifting, *p. 512;* front, *p. 512;* temperature inversion, *p. 514;* condensation nuclei, *p. 516*

18.3 Cloud Types and Precipitation

Key Concepts

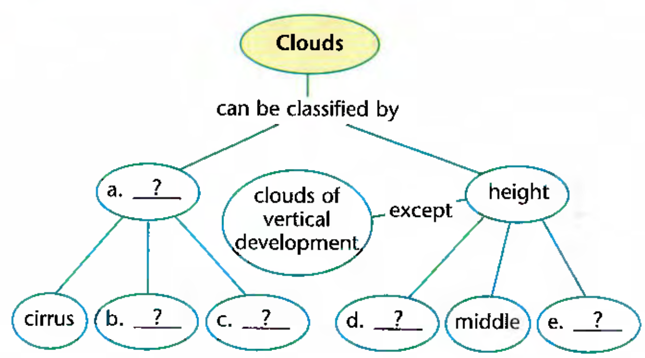
- Clouds are classified on the basis of their form and height.
- Fog is a cloud with its base at or very near the ground.
- In order for precipitation to form, cloud droplets must grow in volume by roughly one million times.
- The type of precipitation that reaches Earth's surface depends on the temperature profile in the lowest few kilometers of the atmosphere.

Vocabulary

cirrus, *p. 517;* cumulus, *p. 517;* stratus, *p. 518;* Bergeron process, *p. 521;* supercooled water, *p. 521;* supersaturated air, *p. 521;* collision-coalescence process, *p. 521*

Thinking Visually

Concept Map Copy the concept map below onto a sheet of paper. Use information from the chapter to complete the concept map.



CHAPTER 18

Assessment

Interactive textbook with assessment at PHSchool.com

Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. What is the general term for water vapor in air?
   a. capacity b. condensation
   c. humidity d. saturation

2. During which process does water vapor change to the liquid state?
   a. condensation b. deposition
   c. melting d. sublimation

3. The ratio of air's actual water-vapor content to the amount of water needed for saturation is the
   a. adiabatic rate. b. dew point.
   c. relative humidity. d. water capacity.

4. What are visible mixtures of tiny water droplets or ice crystals suspended in air?
   a. clouds b. dew
   c. hail d. sleet

5. Air that has a 100 percent relative humidity is said to be
   a. dry. b. saturated.
   c. stable. d. unstable.

6. Compared to clouds, fogs are
   a. a different composition.
   b. at lower altitudes.
   c. colder.
   d. thicker.

7. Which of the following clouds are high, white, and thin?
   a. cirrus b. cumulus
   c. nimbostratus d. stratus

8. Which of the following words means "rainy cloud"?
   a. cirrus b. cumulus
   c. nimbus d. stratus

9. Which of the following substances changes from one state of matter to another at temperatures and pressures experienced at Earth's surface?
   a. carbon dioxide b. nitrogen
   c. oxygen d. water

10. Which of the following forms when supercooled raindrops freeze on contact with solid objects near Earth's surface?
    a. glaze b. hail
    c. sleet d. snow

Understanding Concepts

11. What happens when unstable air is forced to rise?

12. Describe the conditions that might cause convergence.

13. As you drink an ice-cold beverage on a hot day, the outside of the glass becomes wet. Explain why this happens.

14. What is the difference between condensation and precipitation?

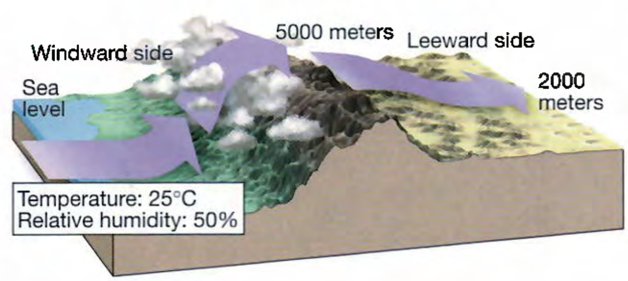
15. Why does air cool when it rises through the atmosphere? What is this type of cooling known as?

16. Write a general statement relating air temperature and the amount of water vapor needed to saturate the air.

17. Describe the difference between clouds and water vapor.

18. List two changes of state for water that cause latent heat to be released.

Use the figure below to answer Questions 19 and 20.



19. Which air-lifting mechanism is shown?

20. Use the dry adiabatic rate of 10°C per kilometer to determine the air temperature on the windward side of the mountains at an altitude of 500 meters.

Assessment *continued*

Critical Thinking

21. **Applying Concepts** What is the physical property of thermals that helps birds of prey? Describe how this physical property helps these birds.

22. **Applying Concepts** Explain how urban areas contribute to localized convective lifting.

23. **Identifying Cause and Effect** Describe how atmospheric stability affects daily weather. Include specific examples.

24. **Applying Concepts** In general, when traveling in foggy conditions, what types of topography should you be most cautious of?

Math Skills

Use the table below to answer Questions 25–27.

Water Vapor Needed for Saturation

Temperature °C	Temperature (°F)	Mass of water vapor per kg of air (g/kg)
−40	(−40)	0.1
−30	(−22)	0.3
−20	(−4)	0.75
−10	(14)	2
0	(32)	3.5
5	(41)	5
10	(50)	7
15	(59)	10
20	(68)	14
25	(77)	20
30	(86)	26.5
35	(95)	35
40	(104)	47

25. **Analyzing Data** According to the table, how much water vapor is required to saturate a kilogram of air at each of the following temperatures?
    a. 40°C
    b. 0°C
    c. −10°C

26. **Calculating** How does the amount of water vapor required to saturate 1 kilogram of air change when it is cooled from 10°C to 0°C?

27. **Calculating** Use the table to determine the relative humidity of air at 15°C when its water vapor content is 7 g/kg.

Concepts in Action

28. **Inferring** Mount Waialeale, Hawaii, is located on a windward mountain slope. A weather station there records the highest average annual rainfall at 1234 cm. Explain what processes could contribute to this extreme rainfall.

29. **Interpreting Illustrations** After studying Figure 2, summarize the processes by which water changes from one state of matter to another. For each case, point out whether heat energy is absorbed or released.

30. **Writing in Science** The amount of precipitation that falls at any particular place and time is controlled by the quantity of moisture in the air and many other factors, which may include (1) an increase in the elevation of the land, (2) a decrease in the area covered by forests and other types of vegetation, and (3) an increase in the percentage of time that the winds blow from an adjacent body of water. Write a paragraph explaining how each of these factors might change the precipitation at a particular location.

Performance-Based Assessment

Designing an Experiment Design and conduct an experiment that explores daily variations in temperature and relative humidity. As a first step, write a clear hypothesis statement. Then plan and design the experiment. Include sample data tables in your plan. Have your teacher approve your plan before you begin.

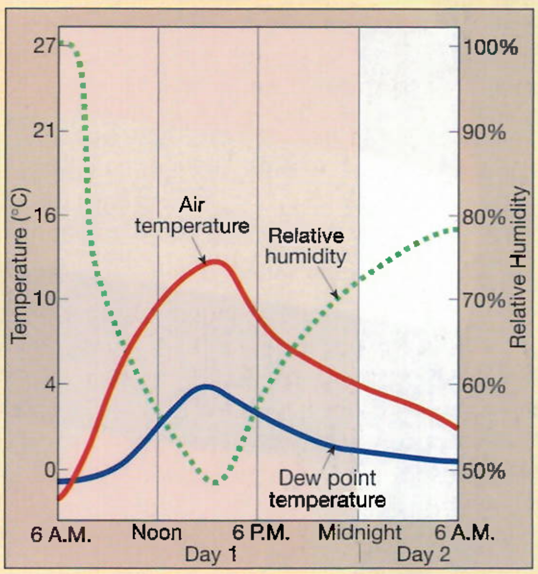
Standardized Test Prep

Test-Taking Tip

When answering a question with a graph, keep these tips in mind:

- Read the question thoroughly to identify what the question is asking.
- Study the title of the graph. This may help you identify what information is available from the graph.
- Examine the graph and note the axes labels.
- Identify the scale of the axes.
- Recall information, equations, definitions, relationship, and so forth that may be required to interpret the graph.
- Once you have chosen your answer, check it against the graph.

Graph 1 Temperature and Relative Humidity



The graph above depicts variations in temperature and relative humidity on a spring day. Which of the following statements is true?

(A) When temperature increases, relative humidity increases.
(B) When temperature decreases, relative humidity decreases.
(C) When temperature increases, relative humidity decreases.
(D) Temperature and relative humidity are not related.

(Answer: C)

Choose the letter that best answers the question or completes the statement.

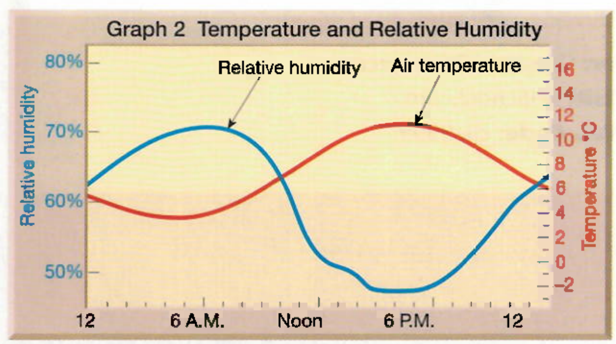
1. The dew point is the temperature at which
   (A) cumulus clouds change to cirrus clouds.
   (B) hailstones are formed.
   (C) liquid water changes to vapor.
   (D) water vapor condenses to liquid.

2. Which process is most important for cloud formation?
   (A) cooling by compression of air
   (B) cooling by contact with a cold surface
   (C) cooling by expansion of air
   (D) cooling by radiation from Earth's surface

3. The process by which water vapor changes directly to a solid is
   (A) condensation.
   (B) deposition
   (C) evaporation.
   (D) sublimation.

Use the graph below to answer Questions 4–5.

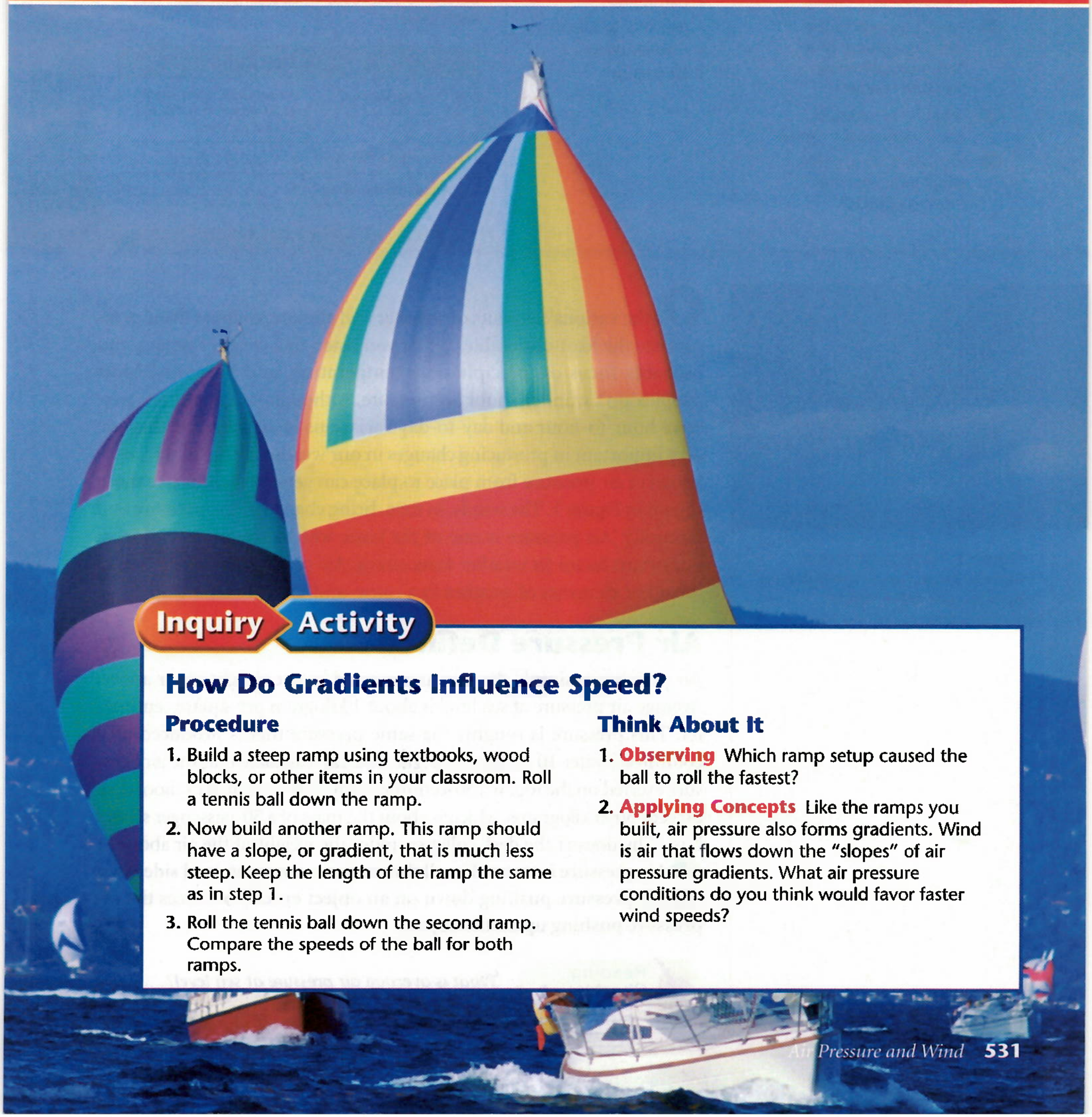
Graph 2 Temperature and Relative Humidity



4. According to this graph, when is relative humidity at its maximum?

5. When does the lowest relative humidity occur?

Chapter Preview



Inquiry Activity

How Do Gradients Influence Speed?

Procedure

1. Build a steep ramp using textbooks, wood blocks, or other items in your classroom. Roll a tennis ball down the ramp.
2. Now build another ramp. This ramp should have a slope, or gradient, that is much less steep. Keep the length of the ramp the same as in step 1.
3. Roll the tennis ball down the second ramp. Compare the speeds of the ball for both ramps.

Think About It

1. **Observing** Which ramp setup caused the ball to roll the fastest?
2. **Applying Concepts** Like the ramps you built, air pressure also forms gradients. Wind is air that flows down the "slopes" of air pressure gradients. What air pressure conditions do you think would favor faster wind speeds?

19.1 Understanding Air Pressure

Reading Focus

Key Concepts

- Describe how air pressure is exerted on objects.
- What happens to the mercury column of a barometer when air pressure changes?
- What is the ultimate energy source for wind?
- How does the Coriolis effect influence free-moving objects?

Vocabulary

- air pressure
- barometer
- pressure gradient
- Coriolis effect
- jet stream

Reading Strategy

Identifying Main Ideas Copy the table below. As you read, write the main ideas for each topic.

Topic	Main Ideas
Air Pressure Defined	Air pressure is the weight of air above. It is exerted in all directions.
Measuring Air Pressure	a. ____?____
Factors Affecting Wind	b. ____?____

Figure 1 These palm trees in Corpus Christi, Texas, are buffeted by hurricane-force winds.

Of the various elements of weather and climate, changes in air pressure are the least noticeable. When you listen to a weather report, you probably focus on precipitation, temperature, and humidity. Most people don't wonder about air pressure. Although you might not perceive hour-to-hour and day-to-day variations in air pressure, they are very important in producing changes in our weather. For example, variations in air pressure from place to place can generate winds like those shown in Figure 1. The winds, in turn, bring change in temperature and humidity. Air pressure is one of the basic weather elements and is an important factor in weather forecasting. Air pressure is closely tied to the other elements of weather in a cause-and-effect relationship.

Air Pressure Defined

Air pressure is simply the pressure exerted by the weight of air above. Average air pressure at sea level is about 1 kilogram per square centimeter. This pressure is roughly the same pressure that is produced by a column of water 10 meters in height. You can calculate that the air pressure exerted on the top of a 50-centimeter-by-100-centimeter school desk exceeds 5000 kilograms, which is about the mass of a 50-passenger school bus. Why doesn't the desk collapse under the weight of the air above it? **Air pressure is exerted in all directions—down, up, and sideways. The air pressure pushing down on an object exactly balances the air pressure pushing up on the object.**

Reading Checkpoint *What is average air pressure at sea level?*

Imagine a tall aquarium that has the same dimensions as the desktop in the previous example. When this aquarium is filled to a height of 10 meters, the water pressure at the bottom equals 1 atmosphere, or 1 kilogram per square centimeter. Now imagine what will happen if this aquarium is placed on top of a student desk so that all the force is directed downward. The desk collapses because the pressure downward is greater than the pressure exerted in the other directions. When the desk is placed inside the aquarium and allowed to sink to the bottom, however, the desk does not collapse in the water because the water pressure is exerted in all directions, not just downward. The desk, like your body, is built to withstand the pressure of 1 atmosphere.

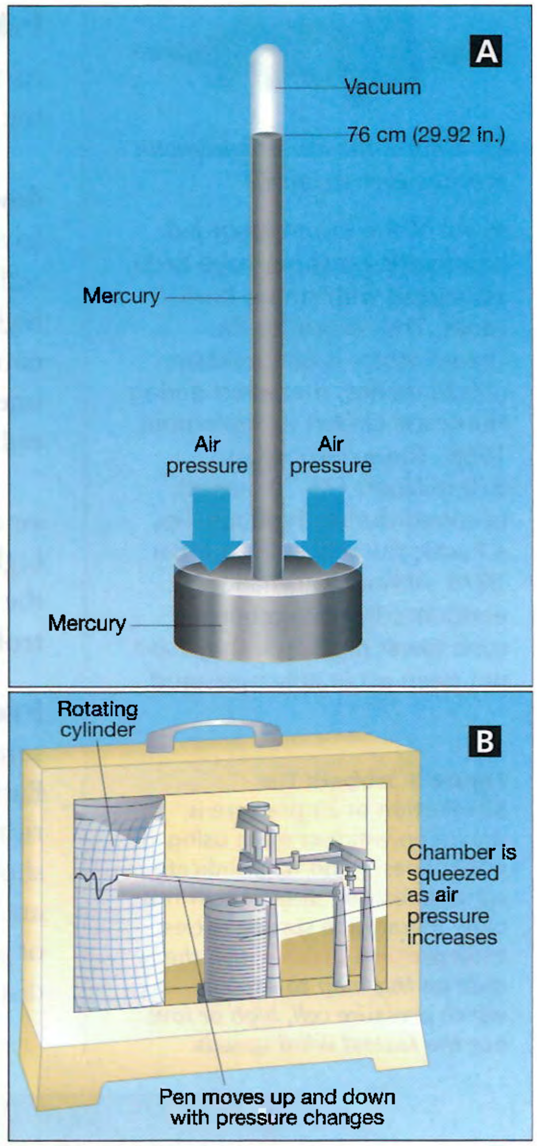


Figure 2 A Mercury Barometer Standard atmospheric pressure at sea level is 29.92 inches of mercury. **B Aneroid Barometer** The recording mechanism provides a continuous record of pressure changes over time. **Applying Concepts** ***Why would a continuous record help weather forecasters?***

Measuring Air Pressure

When meteorologists measure atmospheric pressure, they use a unit called the millibar. Standard sea-level pressure is 1013.2 millibars. You might have heard the phrase "inches of mercury," which is used by the media to describe atmospheric pressure. This expression dates from 1643, when Torricelli, a student of the famous Italian scientist Galileo, invented the mercury barometer. A **barometer** is a device used for measuring air pressure (*bar* = pressure, *metron* = measuring instrument).

Torricelli correctly described the atmosphere as a vast ocean of air that exerts pressure on us and all objects around us. To measure this force, he filled a glass tube, closed at one end, with mercury. He then put the tube upside down into a dish of mercury, as shown in Figure 2A. The mercury flowed out of the tube until the weight of the column was balanced by the pressure that the atmosphere exerted on the surface of the mercury in the dish. In other words, the weight of mercury in the column (tube) equaled the weight of the same size column of air that extended from the ground to the top of the atmosphere.

When air pressure increases, the mercury in the tube rises. When air pressure decreases, so does the height of the mercury column. With some improvements, the mercury barometer is still the standard instrument used today for measuring air pressure.

The need for a smaller and more portable instrument for measuring air pressure led to the development of the aneroid barometer. The aneroid barometer uses a metal chamber with some air removed. This partially emptied chamber is extremely sensitive to variations in air pressure. It changes shape and compresses as the air pressure increases, and it expands as the pressure decreases. One advantage of the aneroid barometer is that it can be easily connected to a recording device, shown in Figure 2B. The device provides a continuous record of pressure changes with the passage of time.

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Q&A

Q *What is the lowest barometric pressure ever recorded?*

A All of the lowest recorded barometric pressures have been associated with strong hurricanes. The record for the United States is 888 millibars (26.20 inches) measured during Hurricane Gilbert in September 1988. The world's record, 870 millibars (25.70 inches), occurred during Typhoon Tip, a Pacific hurricane, in October 1979. Although tornadoes undoubtedly have produced even lower pressures, they have not been accurately measured.

Factors Affecting Wind

As important as vertical motion is, far more air moves horizontally, the phenomenon we call wind. What causes wind?

Wind is the result of horizontal differences in air pressure. Air flows from areas of higher pressure to areas of lower pressure. You may have experienced this flow of air when opening a vacuum-packed can of coffee or tennis balls. The noise you hear is caused by air rushing from the higher pressure outside the can to the lower pressure inside. Wind is nature's way of balancing such inequalities in air pressure. **The unequal heating of Earth's surface generates pressure differences. Solar radiation is the ultimate energy source for most wind.**

If Earth did not rotate, and if there were no friction between moving air and Earth's surface, air would flow in a straight line from areas of higher pressure to areas of lower pressure. But both factors do exist so the flow of air is not that simple. **Three factors combine to control wind: pressure differences, the Coriolis effect, and friction.**

Pressure Differences Wind is created from differences in pressure—the greater these differences are, the greater the wind speed is. Over Earth's surface, variations in air pressure are determined from barometric readings taken at hundreds of weather stations. These pressure data are shown on a weather map, like the one in Figure 3, using isobars. Isobars are lines on a map that connect places of equal air pressure. The spacing of isobars indicates the amount of pressure change occurring over a given distance. These pressure changes are expressed as the **pressure gradient.**

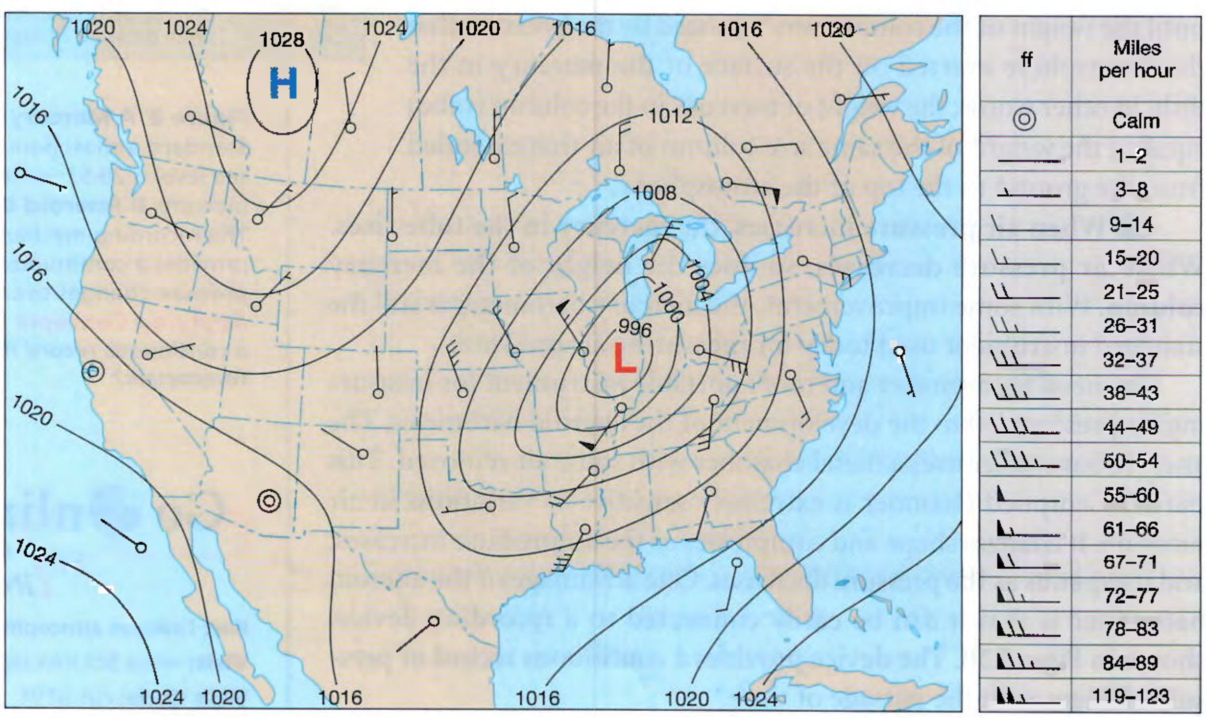


Figure 3 Isobars The distribution of air pressure is shown on weather maps using isobar lines. Wind flags indicate wind speed and direction. Winds blow toward the station circles. **Interpreting Visuals** ***Use the data on this map to explain which pressure cell, high or low, has the fastest wind speeds.***

A steep pressure gradient, like a steep hill, causes greater acceleration of a parcel of air. A less steep pressure gradient causes a slower acceleration. **Closely spaced isobars indicate a steep pressure gradient and high winds. Widely spaced isobars indicate a weak pressure gradient and light winds.** The pressure gradient is the driving force of wind. The pressure gradient has both magnitude and direction. Its magnitude is reflected in the spacing of isobars. The direction of force is always from areas of higher pressure to areas of lower pressure and at right angles to the isobars. Friction affects wind speed and direction. The Coriolis effect affects wind direction only.

Coriolis Effect The weather map in Figure 3 shows typical air movements associated with high- and low-pressure systems. Air moves out of the regions of higher pressure and into the regions of lower pressure. However, the wind does not cross the isobars at right angles as you would expect based solely on the pressure gradient. This change in movement results from Earth's rotation and has been named the **Coriolis effect.**

The Coriolis effect describes how Earth's rotation affects moving objects. All free-moving objects or fluids, including the wind, are deflected to the right of their path of motion in the Northern Hemisphere. In the Southern Hemisphere, they are deflected to the left. The reason for this deflection is illustrated in Figure 4. Imagine the path of a rocket launched from the North Pole toward a target located on the equator. The true path of this rocket is straight, and the path would appear to be straight to someone out in space looking down at Earth. However, to someone standing on Earth, it would look as if the rocket swerved off its path and landed 15 degrees to the west of its target.

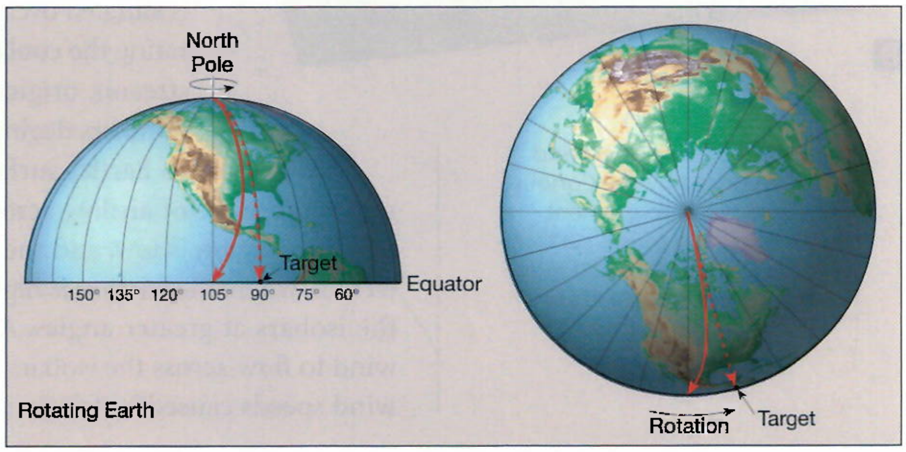


Figure 4 The Coriolis Effect Because Earth rotates 15° each hour, the rocket's path is curved and veers to the right from the North Pole to the equator. **Calculating** ***How many degrees does Earth rotate in one day?***

This slight change in direction happens because Earth would have rotated 15 degrees to the east under the rocket during a one-hour flight. The counterclockwise rotation of the Northern Hemisphere causes path deflection to the right. In the Southern Hemisphere, the clockwise rotation produces a similar deflection, but to the left of the path of motion.

The apparent shift in wind direction is attributed to the Coriolis effect. This deflection: 1) is always directed at right angles to the direction of airflow; 2) affects only wind direction and not wind speed; 3) is affected by wind speed—the stronger the wind, the greater the deflection; and 4) is strongest at the poles and weakens toward the equator, becoming nonexistent at the equator.

Effect of Friction

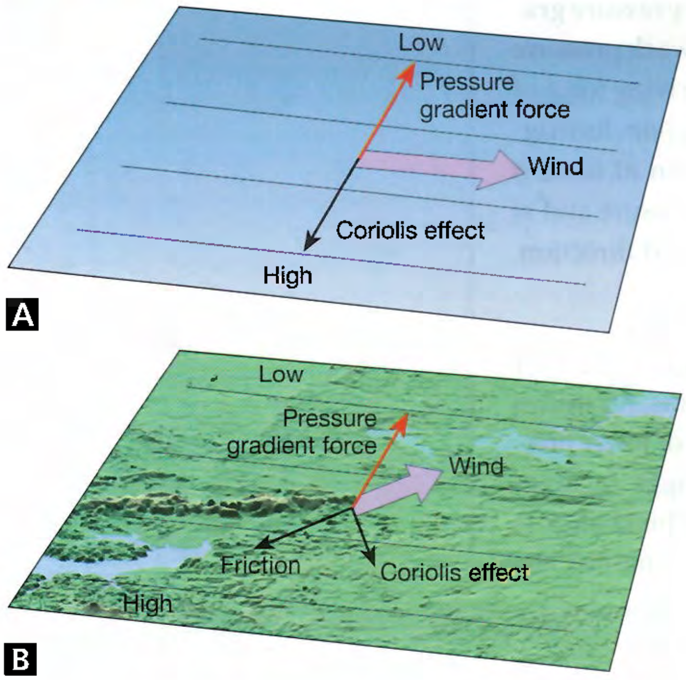


Figure 5 **A** Upper-level wind flow is balanced by the Coriolis effect and pressure gradient forces. **B** Friction causes surface winds to cross isobars and move toward lower pressure areas.

Friction The effect of friction on wind is important only within a few kilometers of Earth's surface. Friction acts to slow air movement, which changes wind direction. To illustrate friction's effect on wind direction, first think about a situation in which friction does not play a role in wind's direction.

When air is above the friction layer, the pressure gradient causes air to move across the isobars. As soon as air starts to move, the Coriolis effect acts at right angles to this motion. The faster the wind speed, the greater the deflection is. The pressure gradient and Coriolis effect balance in high-altitude air, and wind generally flows parallel to isobars, as shown in Figure 5A. The most prominent features of airflow high above the friction layer are the jet streams. **Jet streams** are fast-moving rivers of air that travel between 120 and 240 kilometers per hour in a west-to-east direction. One such jet stream is situated over the polar front, which is the zone separating the cool polar air from warm subtropical air. Jet streams originally were encountered by high-flying bombers during World War II.

For air close to Earth's surface, the roughness of the terrain determines the angle of airflow across the isobars. Over the smooth ocean surface, friction is low, and the angle of airflow is small. Over rugged terrain, where the friction is higher, winds move more slowly and cross the isobars at greater angles. As shown in Figure 5B, friction causes wind to flow across the isobars at angles as great as 45 degrees. Slower wind speeds caused by friction decrease the Coriolis effect.

Section 19.1 Assessment

Reviewing Concepts

1. Why don't objects such as a table collapse under the weight of air above them?
2. Suppose the height of a column in a mercury barometer is decreasing. What is happening?
3. What is the ultimate energy source for most wind?
4. How does the Coriolis effect influence motion of free-moving objects?
5. Why do jet streams flow parallel to isobars?

Critical Thinking

6. **Interpreting illustrations** Study Figures 5A and 5B. Why are the wind arrows drawn to different lengths in these figures?

Connecting Concepts

Solar Radiation Review section 17.3. Describe examples of unequal heating of Earth's atmosphere that could lead to air pressure differences that ultimately influence wind.

19.2 Pressure Centers and Winds

Reading Focus

Key Concepts

- Describe how winds blow around pressure centers in the Northern and Southern Hemispheres.
- What are the air pressure patterns within cyclones and anticyclones?
- How does friction control net flow of air around a cyclone and an anticylone?
- How does the atmosphere attempt to balance the unequal heating of Earth's surface?

Vocabulary

- cyclone
- anticyclone
- trade winds
- westerlies
- polar easterlies
- polar front
- monsoon

Reading Strategy

Comparing and Contrasting Copy the table below. As you read about pressure centers and winds, fill in the table indicating to which hemisphere the concept applies. Use N for Northern Hemisphere, S for Southern Hemisphere, and B for both.

Cyclones rotate counterclockwise.	a. ___?___
Net flow of air is inward around a cyclone.	b. ___?___
Anticyclones rotate counterclockwise.	c. ___?___
Coriolis effect deflects winds to the right.	d. ___?___

Pressure centers are among the most common features on any weather map. By knowing just a few basic facts about centers of high and low pressure, you can increase your understanding of present and forthcoming weather. You can make some weather generalizations based on pressure centers. For example, centers of low pressure are frequently associated with cloudy conditions and precipitation. By contrast, clear skies and fair weather may be expected when an area is under the influence of high pressure, as shown in Figure 6.

Figure 6 These sunbathers at Cape Henlopen, Delaware, are enjoying weather associated with a high-pressure center.

Highs and Lows

Lows, or **cyclones** (*kyklon* = moving in a circle) are centers of low pressure. Highs, or **anticyclones,** are centers of high pressure. **In cyclones, the pressure decreases from the outer isobars toward the center. In anticyclones, just the opposite is the case—the values of the isobars increase from the outside toward the center.**

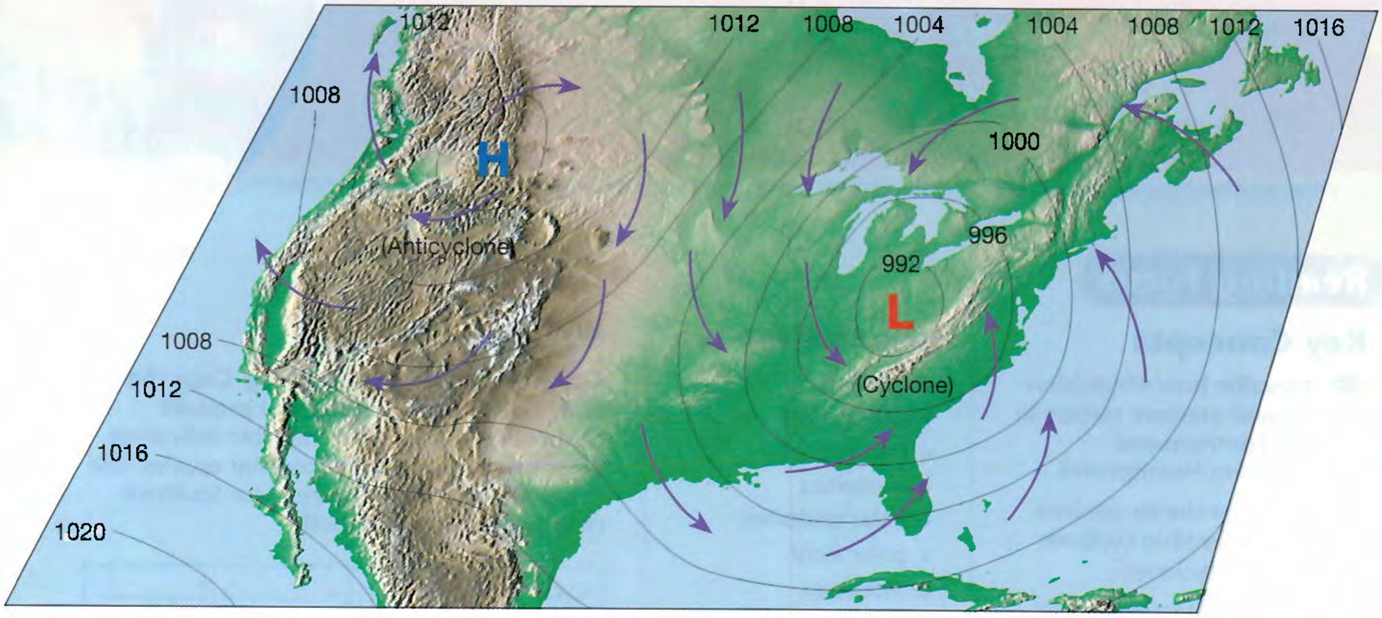


Figure 7 This map shows cyclonic and anticyclonic winds in the Northern Hemisphere.

Cyclonic and Anticyclonic Winds You learned that the two most significant factors that affect wind are the pressure gradient and the Coriolis effect. Winds move from higher pressure to lower pressure and are deflected to the right or left by Earth's rotation. **When the pressure gradient and the Coriolis effect are applied to pressure centers in the Northern Hemisphere, winds blow counterclockwise around a low. Around a high, they blow clockwise.** Notice the wind directions in Figure 7.

In the Southern Hemisphere, the Coriolis effect deflects the winds to the left. Therefore, winds around a low move clockwise. Winds around a high move counterclockwise. **In either hemisphere, friction causes a net flow of air inward around a cyclone and a net flow of air outward around an anticyclone.**

Weather and Air Pressure Rising air is associated with cloud formation and precipitation, whereas sinking air produces clear skies.

Imagine a surface low-pressure system where the air is spiraling inward. Here the net inward movement of air causes the area occupied by the air mass to shrink—a process called horizontal convergence. Whenever air converges (or comes together) horizontally, it must increase in height to allow for the decreased area it now occupies. This increase in height produces a taller and heavier air column. A surface low can exist only as long as the column of air above it exerts less pressure than does the air in surrounding regions. This seems to be a paradox—a low-pressure center causes a net accumulation of air, which increases its pressure.

Reading Checkpoint *With what type of weather is rising air associated?*

Airflow Patterns, Surface and Aloft

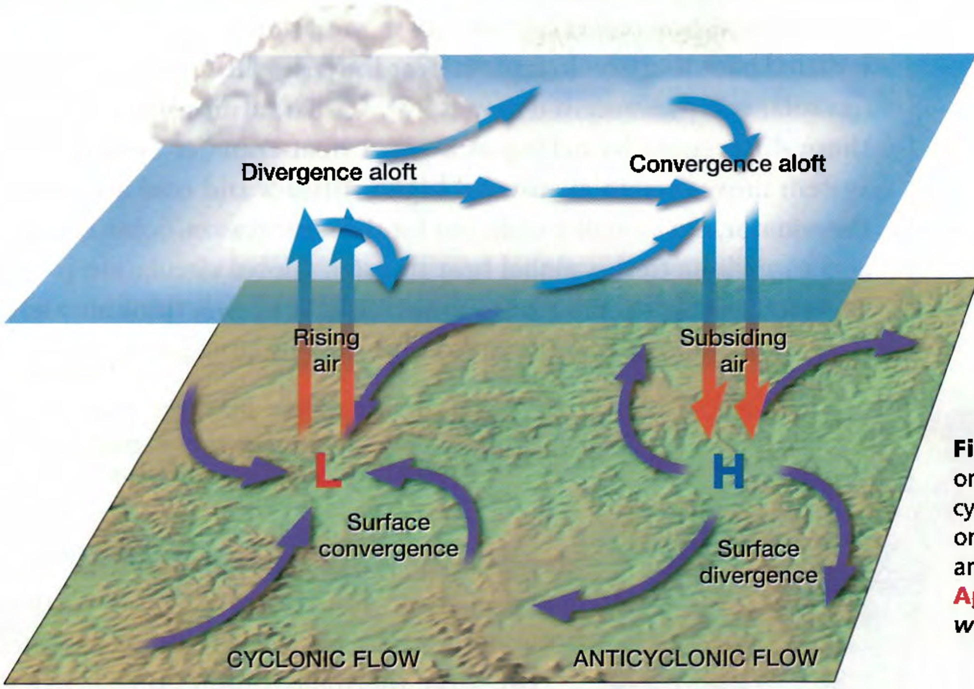


Figure 8 Air spreads out, or diverges, above surface cyclones, and comes together, or converges, above surface anticyclones.
Applying Concepts ***Why is fair weather associated with a high?***

In order for a surface low to exist for very long, converging air at the surface must be balanced by outflows aloft. For example, surface convergence could be maintained if divergence, or the spreading out of air, occurred above the low at a rate equal to the inflow below. Figure 8 shows the relationship between surface convergence (inflow) and divergence (outflow) needed to maintain a low-pressure center. Surface convergence around a cyclone causes a net upward movement. Because rising air often results in cloud formation and precipitation, a low-pressure center is generally related to unstable conditions and stormy weather.

Like cyclones, anticyclones also must be maintained from above. Outflow near the surface is accompanied by convergence in the air above and a general sinking of the air column, as shown in Figure 8.

Weather Forecasting Now you can see why weather reports emphasize the locations and possible paths of cyclones and anticyclones. The villain in these reports is always the low-pressure center, which can produce bad weather in any season. Lows move in roughly a west-to-east direction across the United States, and they require a few days, and sometimes more than a week, for the journey. Their paths can be somewhat unpredictable, making accurate estimation of their movement difficult. Because surface conditions are linked to the conditions of the air above, it is important to understand total atmospheric circulation.

Global Winds

The underlying cause of wind is the unequal heating of Earth's surface. In tropical regions, more solar radiation is received than is radiated back to space. In regions near the poles the opposite is true—less solar energy is received than is lost. **The atmosphere balances these differences by acting as a giant heat-transfer system. This system moves warm air toward high latitudes and cool air toward the equator.** On a smaller scale, but for the same reason, ocean currents also contribute to this global heat transfer. Global circulation is very complex, but you can begin to understand it by first thinking about circulation that would occur on a non-rotating Earth.

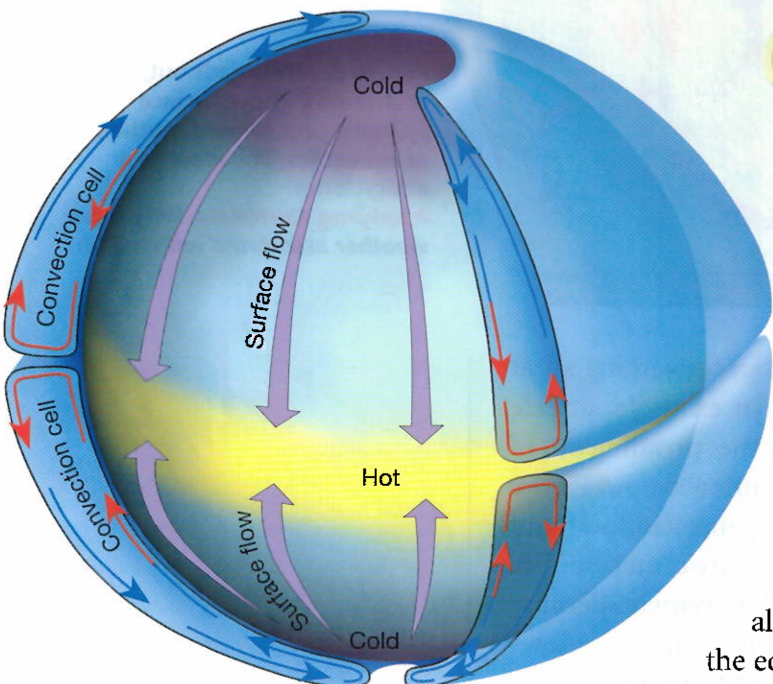


Figure 9 Circulation on a Non-Rotating Earth A simple convection system is produced by unequal heating of the atmosphere.
Relating Cause and Effect ***Why would air sink after reaching the poles?***

Reading Checkpoint ***How does the atmosphere balance the unequal heating of Earth's surface?***

Non-Rotating Earth Model On a hypothetical non-rotating planet with a smooth surface of either all land or all water, two large thermally produced cells would form, as shown in Figure 9. The heated air at the equator would rise until it reached the tropopause—the boundary between the troposphere and the stratosphere. The tropopause, acting like a lid, would deflect this air toward the poles. Eventually, the upper-level airflow would reach the poles, sink, spread out in all directions at the surface, and move back toward the equator. Once at the equator, it would be reheated and begin its journey over again. This hypothetical circulation system has upper-level air flowing toward the pole and surface air flowing toward the equator.

Rotating Earth Model If the effect of rotation were added to the global circulation model, the two-cell convection system would break down into smaller cells. Figure 10 illustrates the three pairs of cells that would carry on the task of redistributing heat on Earth. The polar and tropical cells retain the characteristics of the thermally generated convection described earlier. The nature of circulation at the middle latitudes, however, is more complex.

Near the equator, rising air produces a pressure zone known as the equatorial low—a region characterized by abundant precipitation. As shown in Figure 10, the upper-level flow from the equatorial low reaches 20 to 30 degrees, north or south latitude, and then sinks back toward the surface. This sinking of air and its associated heating due to compression produce hot, arid conditions. The center of this zone of sinking dry air is the subtropical high, which encircles the globe near 30 degrees north and south latitude. The great deserts of Australia, Arabia, and the Sahara in North Africa exist because of the stable dry conditions associated with the subtropical highs.

At the surface, airflow moves outward from the center of the subtropical high. Some of the air travels toward the equator and is deflected by the Coriolis effect, producing the trade winds. **Trade winds** are two belts of winds that blow almost constantly from easterly directions. The trade winds are located between the subtropical highs and the equator. The remainder of the air travels toward the poles and is deflected, generating the prevailing **westerlies** of the middle latitudes. The westerlies make up the dominant west-to-east motion of the atmosphere that characterizes the regions on the poleward side of the subtropical highs. As the westerlies move toward the poles, they encounter the cool polar easterlies in the region of the subpolar low. The **polar easterlies** are winds that blow from the polar high toward the subpolar low. These winds are not constant winds like the trade winds. In the polar region, cold polar air sinks and spreads toward the equator. The interaction of these warm and cool air masses produces the stormy belt known as the **polar front.**

This simplified global circulation is dominated by four pressure zones. The subtropical and polar highs are areas of dry subsiding (sinking) air that flows outward at the surface, producing the prevailing winds. The low-pressure zones of the equatorial and subpolar regions are associated with inward and upward airflow accompanied by clouds and precipitation.

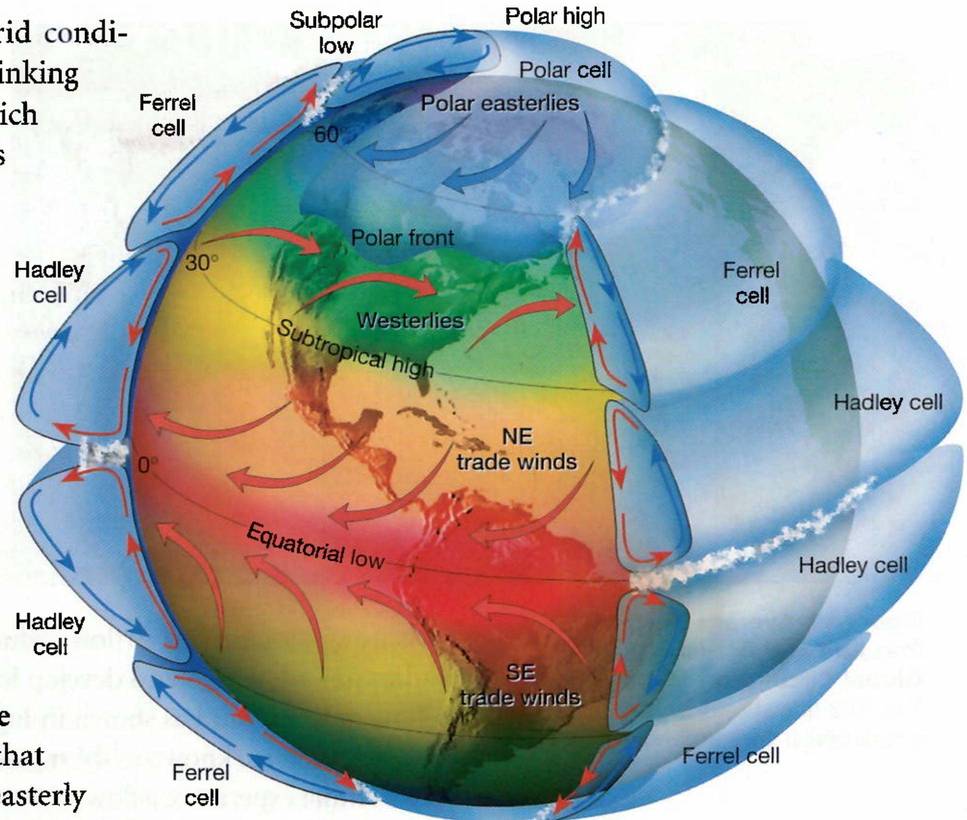


Figure 10 Circulation on a Rotating Earth This model of global air circulation proposes three pairs of cells.
Interpreting Diagrams ***Describe the patterns of air circulation at the equatorial and subpolar lows.***

Reading Checkpoint ***What is the polar front?***

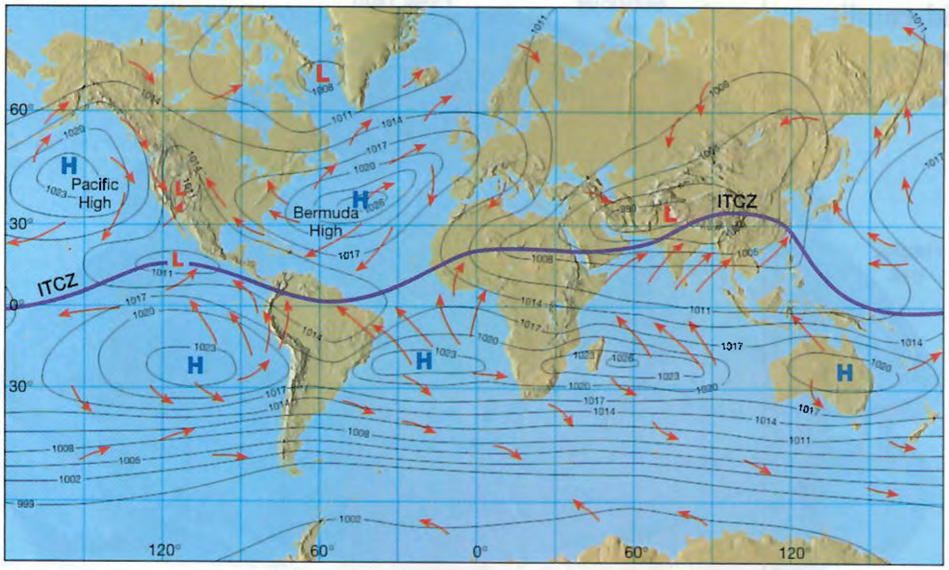


Figure 11 Average Surface Pressure and Associated Global Circulation for July. The ITCZ line stands for the Intertropical Convergence Zone.

Influence of Continents

The only truly continuous pressure belt is the subpolar low in the Southern Hemisphere. Here the ocean is uninterrupted by landmasses. At other latitudes, particularly in the Northern Hemisphere where landmasses break up the ocean surface, large seasonal temperature differences disrupt the pressure pattern. Large landmasses, particularly Asia, become cold in the winter when a seasonal high-pressure system develops. From this high-pressure system, surface airflow is directed off the land. In the summer, landmasses are heated and develop low-pressure cells, which permit air to flow onto the land as shown in Figure 11. These seasonal changes in wind direction are known as the **monsoons.** During warm months, areas such as India experience a flow of warm, water-laden air from the Indian Ocean, which produces the rainy summer monsoon. The winter monsoon is dominated by dry continental air. A similar situation exists to a lesser extent over North America.

Section 19.2 Assessment

Reviewing Concepts

1. Describe how winds blow around pressure centers in the Northern Hemisphere.
2. Compare the air pressure for a cyclone with an anticyclone.
3. How does friction control the net flow of air around a cyclone and an anticyclone?
4. Describe how the atmosphere balances the unequal heating of Earth's surface.
5. What is the only truly continuous pressure belt? Why is it continuous?
6. In general, what type of weather can you expect if a low-pressure system is moving into your area?

Critical Thinking

7. **Identifying Cause and Effect** What must happen in the air above for divergence at the surface to be maintained? What type of pressure center accompanies surface divergence?

Math Practice

8. Examine Figure 7. What is the approximate range of barometric pressure indicated by the isobars on the map? What is the pressure interval between adjacent isobars?

19.3 Regional Wind Systems

Reading Focus

Key Concepts

- What causes local winds?
- Describe the general movement of weather in the United States.
- What happens when unusually strong, warm ocean currents flow along the coasts of Ecuador and Peru?
- How is a La Niña event triggered?

Vocabulary

- prevailing wind
- anemometer
- El Niño

Reading Strategy

Previewing Copy the table below. Before you read, use Figure 17 to locate examples of the driest and wettest regions on Earth. After you read, identify the dominant wind system for each location.

Precipitation	Location	Dominant Wind System
Extremely low	a. ___?___	b. ___?___
Extremely high	c. ___?___	d. ___?___

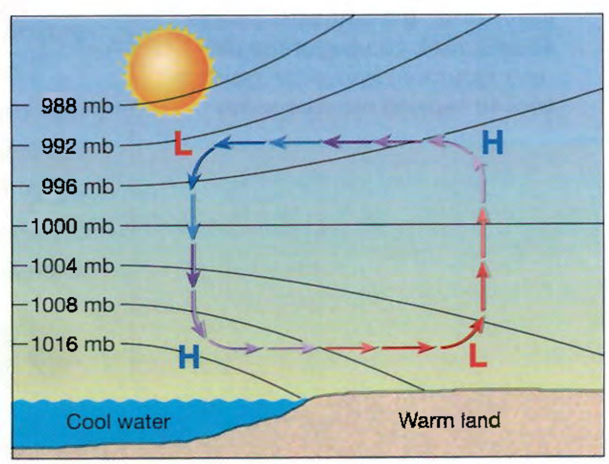
Circulation in the middle latitudes is complex and does not fit the convection system described for the tropics. Between about 30 and 60 degrees latitude, the general west-to-east flow, known as the westerlies, is interrupted by migrating cyclones and anticyclones. In the Northern Hemisphere, these pressure cells move from west to east around the globe.

Local Winds

Small-scale winds produced by a locally generated pressure gradient are known as local winds. **The local winds are caused either by topographic effects or by variations in surface composition—land and water—in the immediate area.**

Land and Sea Breezes In coastal areas during the warm summer months, the land surface is heated more intensely during the daylight hours than an adjacent body of water is heated. As a result, the air above the land surface heats, expands, and rises, creating an area of lower pressure. As shown in Figure 12, a sea breeze then develops because cooler air over the water at higher pressure moves toward the warmer land and low pressure air. The breeze starts developing shortly before noon and generally reaches its greatest intensity during the mid- to late afternoon. These relatively cool winds can be a moderating influence on afternoon temperatures in coastal areas.

Figure 12 Sea Breeze During daylight hours, the air above land heats and rises, creating a local zone of lower air pressure.



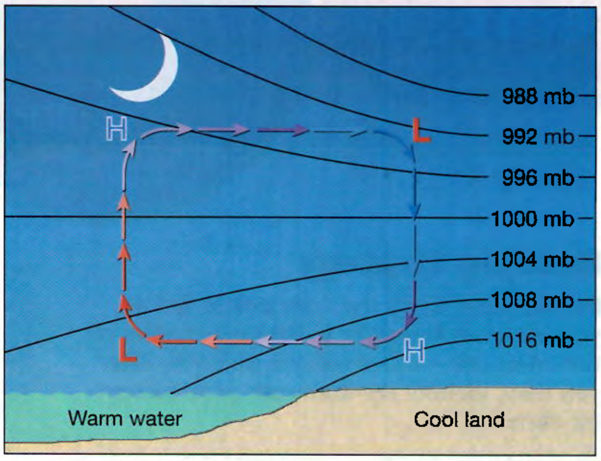


Figure 13 Land Breeze At night, the land cools more rapidly than the sea, generating an offshore flow called a land breeze. **Inferring** ***How would the isobar lines be oriented if there was no air pressure change across the land–water boundary?***

At night, the reverse may take place. The land cools more rapidly than the sea, and a land breeze develops, as shown in Figure 13. The cooler air at higher pressures over the land moves to the sea, where the air is warmer and at lower pressures. Small-scale sea breezes also can develop along the shores of large lakes. People who live in a city near the Great Lakes, such as Chicago, recognize this lake effect, especially in the summer. They are reminded daily by weather reports of the cool temperatures near the lake as compared to warmer outlying areas.

Valley and Mountain Breezes A daily wind similar to land and sea breezes occurs in many mountainous regions. During daylight hours, the air along the slopes of the mountains is heated more intensely than the air at the same elevation over the valley floor. Because this warmer air on the mountain slopes is less dense, it glides up along the slope and generates a valley breeze, as shown in Figure 14A. The occurrence of these daytime upslope breezes can often be identified by the cumulus clouds that develop on adjacent mountain peaks.

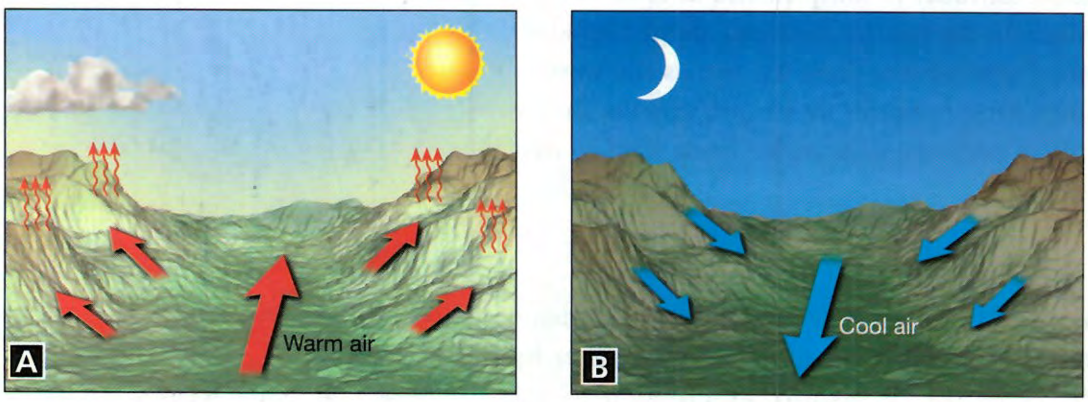


Figure 14 A Valley Breeze Heating during the day generates warm air that rises from the valley floor. **B Mountain Breeze** After sunset, cooling of the air near mountain slopes can result in cool air moving into the valley.

After sunset, the pattern may reverse. The rapid cooling of the air along the mountain slopes produces a layer of cooler air next to the ground. Because cool air is denser than warm air, it moves downslope into the valley. Such a movement of air, illustrated in Figure 14B, is called a mountain breeze. In the Grand Canyon at night, the sound of cold air rushing down the sides of the canyon can be louder than the sound of the Colorado River below.

The same type of cool air drainage can occur in places that have very modest slopes. The result is that the coldest pockets of air are usually found in the lowest spots. Like many other winds, mountain and valley breezes have seasonal preferences. Although valley breezes are most common during the warm season when solar heating is most intense, mountain breezes tend to be more dominant in the cold season.

Reading Checkpoint ***What type of local wind can form in the Grand Canyon at night?***

How Wind Is Measured

Two basic wind measurements—direction and speed—are particularly important to the weather observer. Winds are always labeled by the direction from which they blow. A north wind blows from the north toward the south. An east wind blows from the east toward the west. The instrument most commonly used to determine wind direction is the wind vane, shown in the upper right of Figure 15. Wind vanes commonly are located on buildings, and they always point into the wind. The wind direction is often shown on a dial connected to the wind vane. The dial indicates wind direction, either by points of the compass—N, NE, E, SE, etc.—or by a scale of 0° to 360°. On the degree scale, 0° or 360° are north, 90° is east, 180° is south, and 270° is west.

Figure 15 Wind Vane and Cup Anemometer
Interpreting Photographs ***How does the position of a wind vane tell you which direction the wind is blowing?***

Reading Checkpoint *Toward which direction does a SE wind blow?*

Wind Direction When the wind consistently blows more often from one direction than from any other, it is called a **prevailing wind.** Recall the prevailing westerlies that dominate circulation in the middle latitudes. **In the United States, the westerlies consistently move weather from west to east across the continent.** Along within this general eastward flow are cells of high and low pressure with the characteristic clockwise and counterclockwise flows. As a result, the winds associated with the westerlies, as measured at the surface, often vary considerably from day to day and from place to place. In contrast, the direction of airflow associated with the trade winds is much more consistent.

Wind Speed Shown in the upper left of Figure 15, a cup **anemometer** (*anemo* = wind, *metron* = measuring instrument) is commonly used to measure wind speed. The wind speed is read from a dial much like the speedometer of an automobile. Places where winds are steady and speeds are relatively high are potential sites for tapping wind energy.

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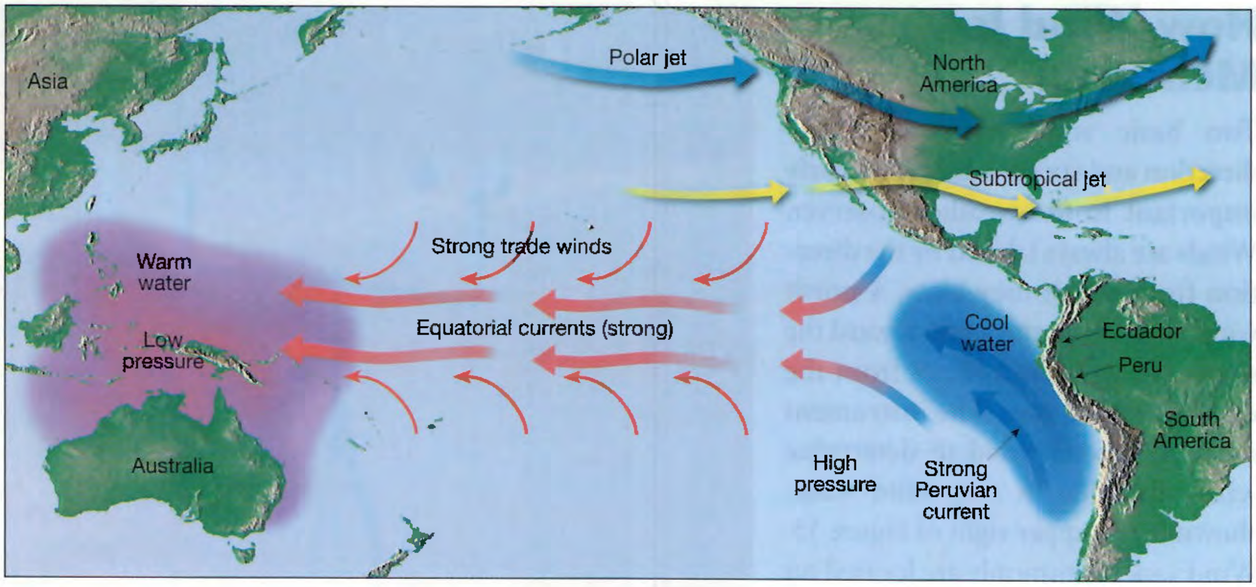

Figure 16 Normal Conditions Trade winds and strong equatorial ocean currents flow toward the west.

El Niño and La Niña

Look at Figure 16. The cold Peruvian current flows toward the equator along the coasts of Ecuador and Peru. This flow encourages upwelling of cold nutrient-filled waters that are the primary food source for millions of fish, particularly anchovies. Near the end of the year, however, a warm current that flows southward along the coasts of Ecuador and Peru replaces the cold Peruvian current. During the nineteenth century, the local residents named this warm current El Niño ("the child") after the Christ child because it usually appeared during the Christmas season. Normally, these warm countercurrents last for a few weeks and then give way to the cold Peruvian flow again.

El Niño

At irregular intervals of three to seven years, these warm countercurrents become unusually strong and replace normally cold offshore waters with warm equatorial waters. Scientists use the term **El Niño** for these episodes of ocean warming that affect the eastern tropical Pacific.

The onset of El Niño is marked by abnormal weather patterns that drastically affect the economies of Ecuador and Peru. As shown in Figure 17, these unusually strong undercurrents accumulate large quantities of warm water that block the upwelling of colder, nutrient-filled water. As a result, the anchovies starve, devastating the local fishing industry. At the same time, some inland areas that are normally arid receive an abnormal amount of rain. Here, pastures and cotton fields have yields far above the average. These climatic fluctuations have been known for years, but they were originally considered local phenomena. It now is understood that El Niño is part of the global circulation and that it affects the weather at great distances from Peru and Ecuador.

When an El Niño began in the summer of 1997, forecasters predicted that the pool of warm water over the Pacific would displace the

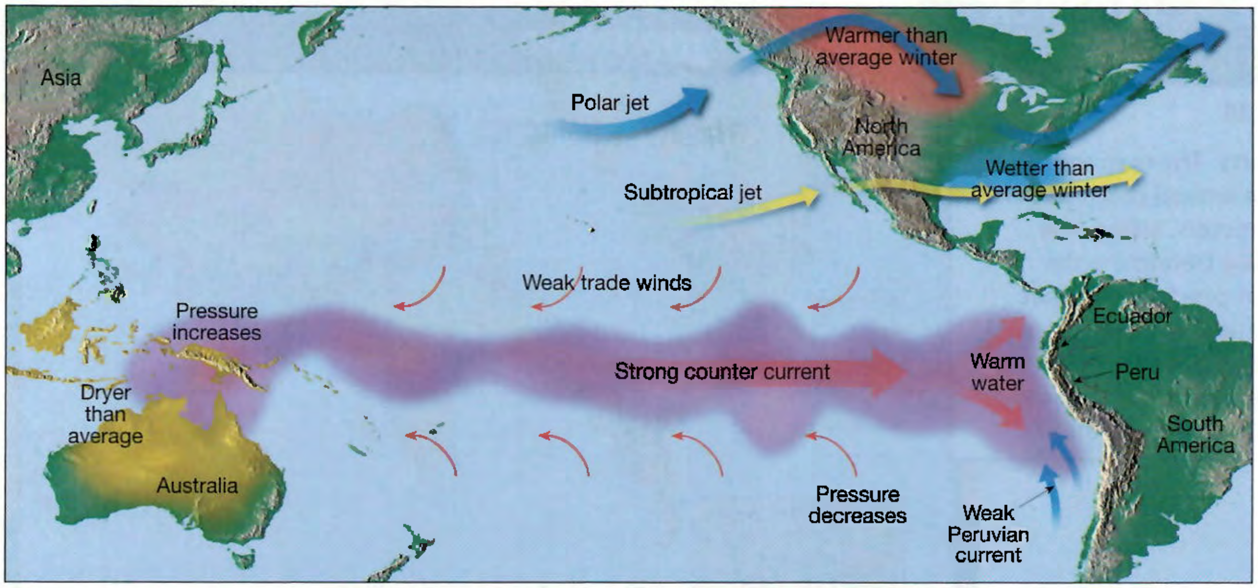

Figure 17 El Niño Warm countercurrents cause reversal of pressure patterns in the western and eastern Pacific.

paths of both the subtropical and midlatitude jet streams, as shown in Figure 17. The jet streams steer weather systems across North America. As predicted, the subtropical jet brought rain to the Gulf Coast. Tampa, Florida, received more than three times its normal winter precipitation. The mid-latitude jet pumped warm air far north into the continent. As a result, winter temperatures west of the Rocky Mountains were significantly above normal.

Reading Checkpoint ***What is an El Niño and what effect does it have on weather?***

La Niña The opposite of El Niño is an atmospheric phenomenon known as La Niña. Once thought to be the normal conditions that occur between two El Niño events, meteorologists now consider La Niña an important atmospheric phenomenon in its own right. **Researchers have come to recognize that when surface temperatures in the eastern Pacific are colder than average, a La Niña event is triggered that has a distinctive set of weather patterns.** A typical La Niña winter blows colder than normal air over the Pacific Northwest and the northern Great Plains. At the same time, it warms much of the rest of the United States. The Northwest also experiences greater precipitation during this time. During the La Niña winter of 1998–99, a world-record snowfall for one season occurred in Washington State. La Niña impact can also increase hurricane activity. A recent study concluded that the cost of hurricane damages in the United States is 20 times greater in La Niña years as compared to El Niño years.

The effects of both El Niño and La Niña on world climate are widespread and vary greatly. These phenomena remind us that the air and ocean conditions of the tropical Pacific influence the state of weather almost everywhere.

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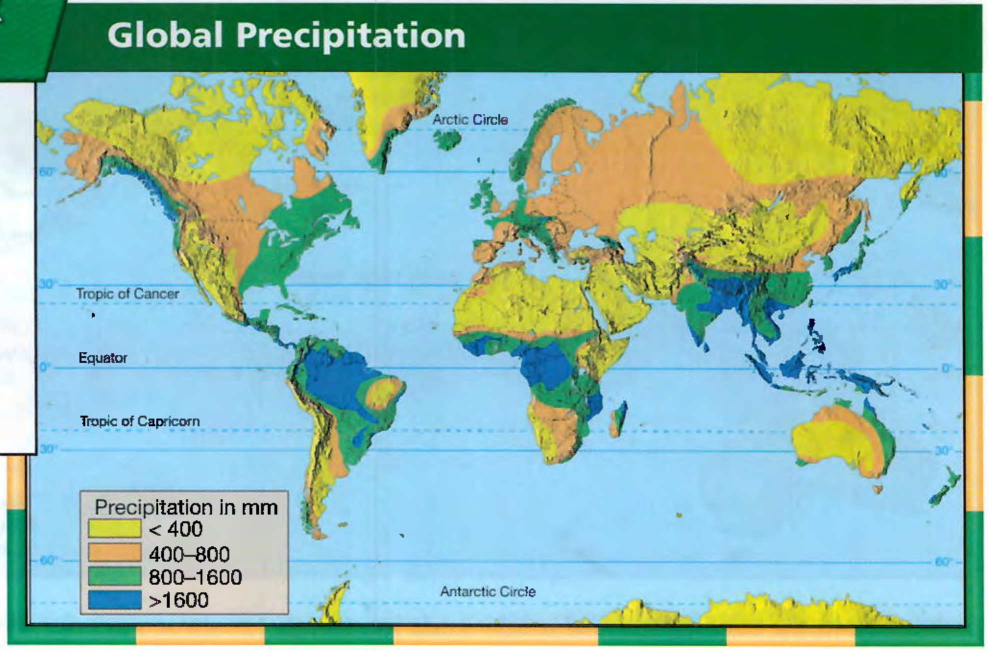
MAP MASTER™ Skills Activity

Figure 18

Regions The map shows average annual precipitation in millimeters. **Using the Map Key** Determine the range of precipitation that dominates Northern Africa. **Identify Causes** Which weather pattern influences precipitation in this area?



Global Distribution of Precipitation

Figure 18 shows that the tropical region dominated by the equatorial low is the rainiest region on Earth. It includes the rain forests of the Amazon basin in South America and the Congo basin in Africa. In these areas, the warm, humid trade winds converge to yield abundant rainfall throughout the year. In contrast, areas dominated by the subtropical high-pressure cells are regions of extensive deserts. Variables other than pressure and wind complicate the pattern. For example, the interiors of large land masses commonly experience decreased precipitation. However, you can explain a lot about global precipitation if you apply your knowledge of global winds and pressure systems.

Section 19.3 Assessment

Reviewing Concepts

1. What are local winds, and how are they caused?
2. Describe the general movement of weather in the United States.
3. What happens when strong, warm countercurrents flow along the coasts of Ecuador and Peru?
4. How is a La Niña event recognized?
5. What two factors mainly influence global precipitation?

Critical Thinking

6. **Interpreting illustrations** Study Figure 17. How could air pressure changes influence weather patterns in this region?

Writing in Science

Compare-Contrast Paragraph Write a paragraph comparing the features and effects of El Niño and La Niña. Include specific weather patterns associated with each phenomenon.

understanding **EARTH**

Tracking El Niño from Space

The images in Figure 19 show the progression of the 1997–98 El Niño. They were derived from data collected by the satellite TOPEX/Poseidon.* This satellite bounces radar signals off the ocean surface to precisely measure the distance between the satellite and the sea surface. When combined with high-precision data from the Global Positioning System (GPS) of satellites, maps of sea-surface topography like these can be produced. These maps show the topography of the sea surface. The presence of hills indicates warmer-than-average water, and the areas of low topography, or valleys, indicate cooler-than-normal water. Using water topography, scientists can determine the speed and direction of surface ocean currents.

The colors in these images show sea-level height relative to the average. When you focus on the images, remember that hills are warm colors and valleys are cool colors. The white and red areas indicate places of higher-than-normal sea-surface heights. In the white areas, the sea surface is between 14 and 32 centimeters above normal. In the red areas, sea level is elevated by about 10 centimeters. Green areas indicate average conditions, whereas purple shows zones that are at least 18 centimeters below average sea level.

The images show the progression of the large warm-water mass from west to east across the equatorial Pacific Ocean. At its peak in November 1997, the surface area covered by the warm water mass was about one and one half times the size of the 48 contiguous United States. The amount of warm water added to the eastern Pacific with a temperature between 21°C and 30°C was about 30 times the combined volume of the water in all of the United States Great Lakes.

**Source: NASA's Goddard Space Flight Center*

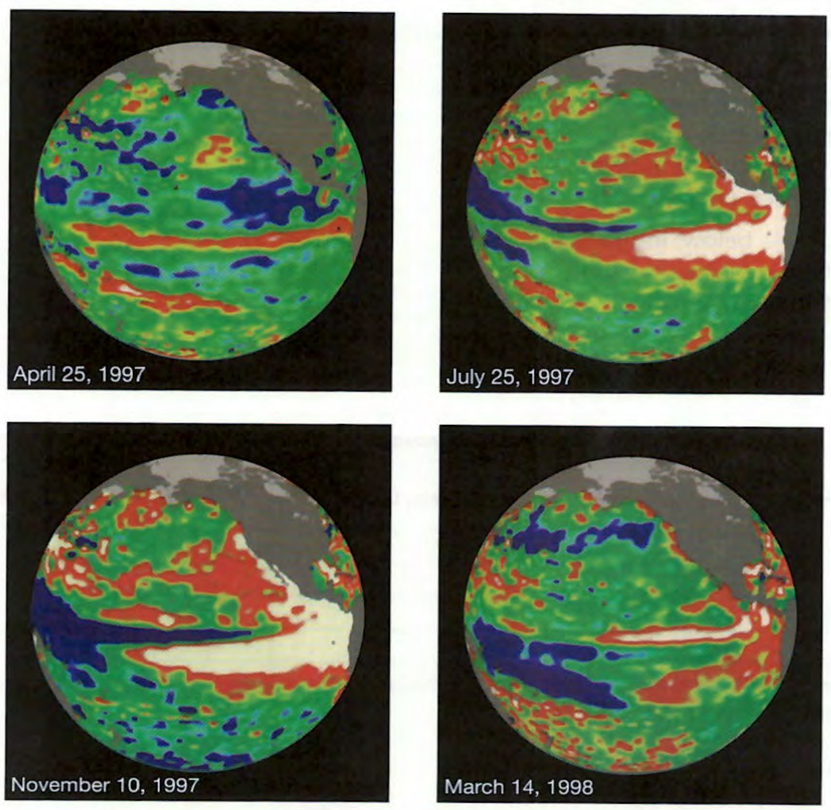


Figure 19 Progression of the 1997–98 El Niño

Exploration Lab

Observing Wind Patterns

Atmospheric pressure and wind are two elements of weather that are closely interrelated. Most people don't usually pay close attention to the pressure given in a weather report. However, pressure differences in the atmosphere drive the winds that often bring changes in temperature and moisture.

Problem

How can surface barometric pressure maps be interpreted?

Materials

- 1 copy each of Figure 1 and Figure 2
- paper
- pencil

Skills

Observing, Analyzing Data, Calculating

Procedure

1. Look at Figure 2. This map shows global wind patterns and average global barometric pressure for the month of January.
2. Examine the individual pressure cells in Figure 2. Then complete the diagrams in your copy of Figure 1. Label the isobars with appropriate pressures, and use arrows to indicate the surface air movement in each pressure cell.
3. Copy the data table below. Indicate the movements of air in high and low pressure cells by completing the table.

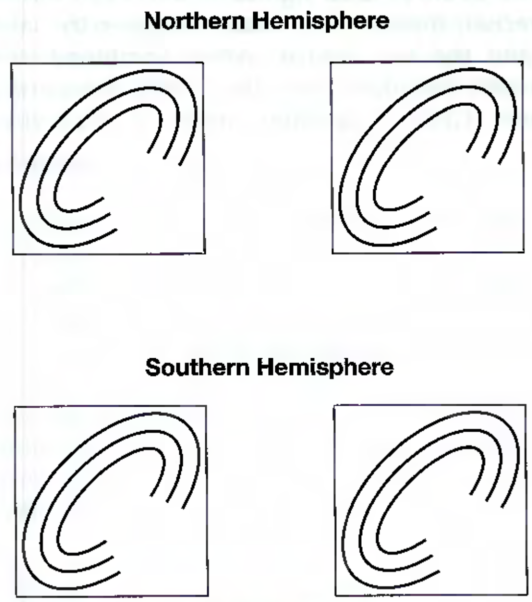


Figure 1

Air Movement in Pressure Cells Data Table

Air Movement	N. Hem. High	N. Hem. Low	S. Hem High	S. Hem. Low
into/out of				
rises/sinks				
rotates CW/CCW*				

* CW = clockwise; CCW = counterclockwise

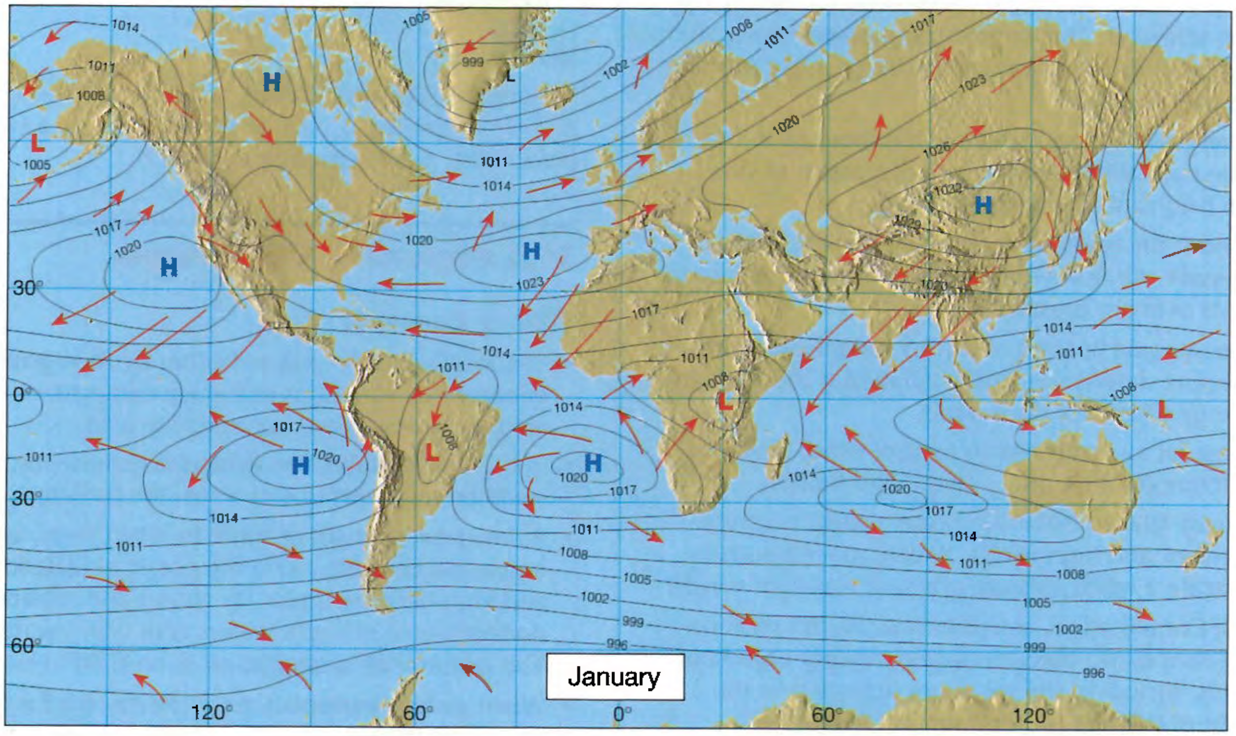


Figure 2

Analyze and Conclude

1. **Comparing and Contrasting** Summarize the differences and similarities in surface air movement between a Northern Hemisphere cyclone and a Southern Hemisphere cyclone.
2. **Interpreting Illustrations** Use your textbook as a reference to locate and write the name of each global wind belt at the appropriate location on your copy of the map in Figure 2. Also indicate the region of the polar front.
3. **Applying** Label areas on your copy of Figure 2 where you would expect high wind speeds to occur.
4. **Applying** Label areas on your copy of Figure 2 where circulation is most like the idealized global wind model for a rotating Earth. Explain why this region on Earth is so much like the model.

CHAPTER 19

Study Guide

19.1 Understanding Air Pressure

Key Concepts

- Air pressure is exerted in all directions—down, up, and sideways. The air pressure pushing down on an object exactly balances the air pressure pushing up on the object.
- When air pressure increases, the mercury in the tube rises. When air pressure decreases, so does the height of the mercury column.
- Wind is the result of horizontal differences in air pressure. Air flows from areas of higher pressure to areas of lower pressure.
- The unequal heating of Earth's surface generates pressure differences. Solar radiation is the ultimate energy source for most wind.
- Three factors combine to control wind: pressure differences, the Coriolis effect, and friction.
- Closely spaced isobars indicate a steep pressure gradient and high winds. Widely spaced isobars indicate a weak pressure gradient and light winds.
- The Coriolis effect describes how Earth's rotation affects moving objects. All free-moving objects or fluids, including the wind, are deflected to the right of their path of motion in the Northern Hemisphere. In the Southern Hemisphere, they are deflected to the left.

Vocabulary

air pressure, *p. 532;* barometer *p. 533;* pressure gradient, *p. 534;* Coriolis effect, *p. 535;* jet stream, *p. 536*

19.2 Pressure Centers and Winds

Key Concepts

- In the Northern Hemisphere, winds blow inward and counterclockwise around a low. Around a high, they blow outward and clockwise.
- In cyclones, the pressure decreases from the outer isobars toward the center. In anticyclones, just the opposite is the case—the values of the isobars increase from the outside toward the center.
- In either hemisphere, pressure difference, the Coriolis effect, and friction causes a net flow of air inward around a cyclone and a net flow of air outward around an anticyclone.
- The atmosphere balances differences in solar radiation in the tropics and the poles by acting as a giant heat-transfer system. This system moves warm air toward high latitudes and cool air toward the equator.

Vocabulary

cyclone, *p. 538;* anticyclone, *p. 538;* trade winds, *p. 541;* westerlies, *p. 541;* polar easterlies, *p. 541;* polar front, *p. 541;* monsoon, *p. 542*

19.3 Regional Wind Systems

Key Concepts

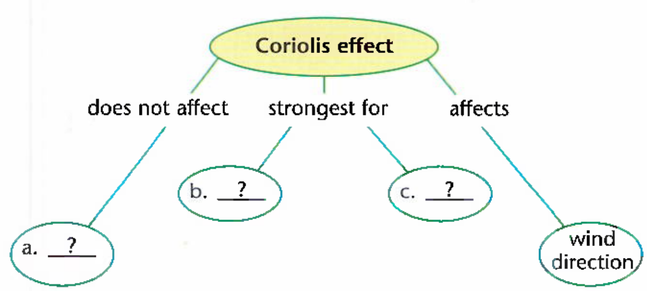
- The local winds are caused either by topographic effects or by variations in surface composition—land and water—in the immediate area.
- In the United States, the westerlies consistently move weather from west to east across the continent.
- At irregular intervals of three to seven years, warm equatorial currents along the coasts of Ecuador and Peru become unusually strong and replace normally cold offshore waters with warm waters. This occurrence is referred to as an El Niño event.
- When surface temperatures in the eastern Pacific are colder than average, a La Niña event is triggered that has a distinctive set of weather patterns.

Vocabulary

prevailing wind, *p. 545;* anemometer, *p. 545;* El Niño, *p. 546;* La Niña, *p. 547*

Thinking Visually

Concept Map Copy the concept map below onto a sheet of paper. Use information from the chapter to complete the concept map.



Assessment

Interactive textbook with assessment at PHSchool.com

Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. The mercurial barometer was invented by
   a. Galileo. **b.** Newton. **c.** Torricelli. **d.** Watt.
2. The force exerted by the air above is called
   a. air pressure. **b.** convergence. **c.** divergence. **d.** the Coriolis effect.
3. What are centers of low pressure called?
   a. air masses **b.** anticyclones **c.** cyclones **d.** jet streams
4. Variations in air pressure from place to place are the principal cause of
   a. clouds. **b.** lows. **c.** hail. **d.** wind.
5. In the winter, large landmasses often develop a seasonal
   a. high-pressure system.
   b. low-pressure system.
   c. typhoon.
   d. trade wind.
6. A sea breeze is most intense
   a. during mid- to late afternoon.
   b. in the late morning.
   c. late in the evening.
   d. at sunrise.
7. What is the pressure zone that is associated with rising air near the equator?
   a. equatorial low **b.** equatorial high **c.** subtropical low **d.** subtropical high
8. What are high-altitude, high-velocity winds?
   a. cyclonic currents **b.** isobars **c.** jet streams **d.** pressure gradients
9. Where is deflection of wind due to the Coriolis effect the strongest?
   a. near the equator **b.** in the midlatitudes **c.** near the poles **d.** near the westerlies
10. In what stormy region do the westerlies and polar easterlies converge?
    a. equatorial low **b.** subpolar high **c.** polar front **d.** subtropical front

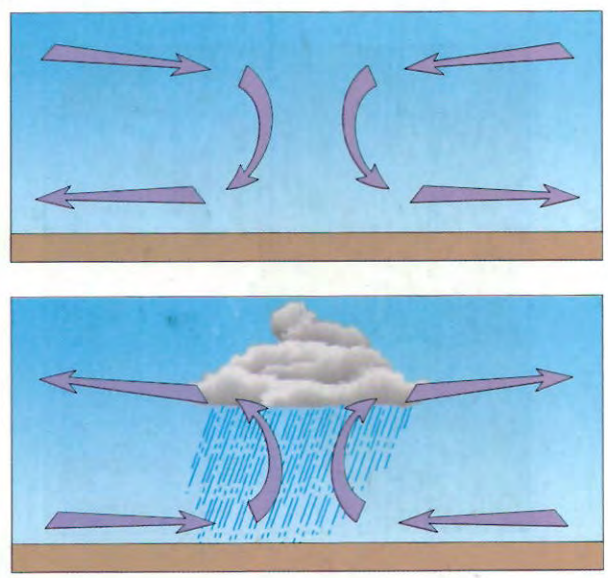
Understanding Concepts

11. Describe how an aneroid barometer works.
12. Write a general statement relating the spacing of isobars to wind speed.
13. Describe the weather that usually accompanies a
    a. drop in barometric pressure.
    b. rise in barometric pressure.
14. How does the Coriolis effect modify air movement in the Southern Hemisphere?
15. The trade winds originate from which pressure zone?
16. List and briefly describe three examples of local winds.
17. On a wind vane with a degree scale, which type of wind is indicated by 90 degrees?

Use the figure below to answer Questions 18–20.

A

B



18. In diagram A, what type of surface air flow is shown?
19. What type of surface pressure system is illustrated in diagram B?
20. Select the diagram in which air at the surface first begins to pile up.

Assessment *continued*

Critical Thinking

21. **Predicting** If you are in the Northern Hemisphere and are directly west of the center of a cyclone, what most likely will be the wind direction? What will the wind direction be if you are west of an anticyclone in the Northern Hemisphere?

22. **Applying Concepts** If you were looking for a location to place a wind turbine to generate electricity, how would you use the spacing of isobars in making your decision?

23. **Hypothesizing** What differences in the biosphere would you predict for areas dominated by low-pressure systems compared to those dominated by high-pressure systems?

Math Skills

Use the illustration below to answer Questions 24–26.

24. **Analyzing Data** According to the map, which winds dominate this region?

25. **Measuring** About what percent of the time do winds blow from the east?

26. **Calculating** Determine the approximate percent of time that winds blow from either the west or the northwest in this area.

Concepts in Action

27. **Predicting** How might a La Niña event impact the weather in your area?

28. **Applying Concepts** Mercury is 13 times heavier than water. If you built a barometer using water rather than mercury, how tall would it have to be to record standard sea-level pressure? Express your answer in centimeters. (Hint: How many centimeters of mercury represent standard sea-level pressure?)

29. **Interpreting Illustrations** After studying Figure 16, explain the relationship between water temperature and the type of air pressure system that develops.

Performance-Based Assessment

Observing For two weeks, keep a daily air pressure, wind, and precipitation log in your science notebook. Be sure to note any changes, and note if any of the changes occur over the course of a single day. At the end of two weeks, organize your information into a data table. Prepare a short summary that includes any patterns you determine among these variables. Report the results orally to your class.

Standardized Test Prep

Test-Taking Tip

Anticipate the Answer
When answering multiple choice questions, a useful strategy is to cover up the given answers and supply your own answer. Then compare your answer with those listed and select the one that most closely matches.

Practice anticipating the answer in Questions 1–4.

Choose the letter that best answers the question or completes the statement.

1. The Sahara in North Africa and the Australian desert, as well as others, are associated with which pressure zone?
(A) equatorial low
(B) polar high
(C) subpolar low
(D) subtropical high

2. What does a steep air pressure gradient cause?
(A) high winds
(B) light winds
(C) variable winds
(D) north winds

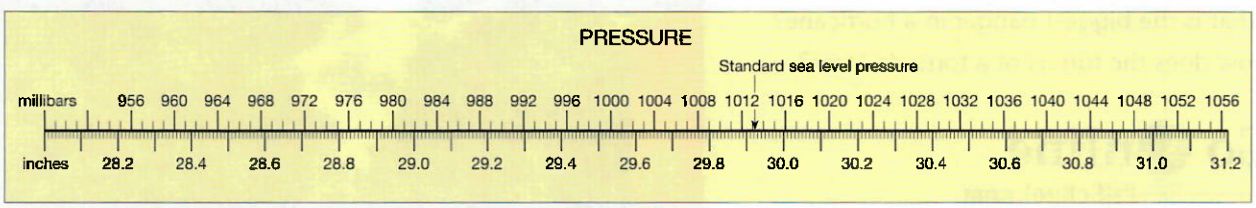
3. Low-pressure systems are usually associated with
(A) descending air.
(B) diverging surface winds.
(C) clear weather.
(D) precipitation.

4. A sea breeze usually originates during the
(A) evening and flows toward the land.
(B) day and flows toward the land.
(C) evening and flows toward the water.
(D) day and flows toward the water.

Use the illustration below to answer Questions 5 and 6.

5. Using this scale, determine the standard sea level pressure in millibars and inches of mercury. Express your answers to the nearest millibar and to the nearest hundredth of an inch.

6. What is the corresponding pressure, in millibars, for a pressure measurement of 30.30 inches of mercury?



CHAPTER 20

Weather Patterns and Severe Storms

CONCEPTS in Action

Application Lab
Middle-Latitude Cyclones

How the Earth Works
Winds and Storms

GEODe Earth Science
The Atmosphere
↳ Basic Weather Patterns

Discovery Channel School

Video Field Trip

Violent Weather

Take a stormy field trip with Discovery Channel and find out how hurricanes and tornadoes occur. Answer the following questions after watching the video.

1. What is the biggest danger in a hurricane?
2. How does the funnel of a tornado form?

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Lightning forms suddenly when negative charges near the bottom of a cloud flow toward the positively charged ground. ▶

20.1 Air Masses

Reading Focus

Key Concepts

- What is an air mass?
- What happens as an air mass moves over an area?
- How are air masses classified?
- Which air masses influence much of the weather in North America?
- Why do continental tropical air masses have little effect on weather in North America?

Vocabulary

- air mass

Reading Strategy

Building Vocabulary Copy the table. As you read this section, write a definition for each of the terms in the table. Refer to the table as you read the rest of the chapter.

Term	Definition
Air mass	a. ___?___
Source region	b. ___?___
Polar air mass	c. ___?___
Tropical air mass	d. ___?___
Continental air mass	e. ___?___
Maritime air mass	f. ___?___

Figure 1 Tornado Damage in Kansas The force of the wind during a tornado was strong enough to drive a piece of metal into the utility pole.

Severe storms are among nature's most destructive forces. Every spring, for example, newspapers and newscasts report the damage caused by tornadoes, which are short but violent windstorms that move quickly over land. The forces associated with these storms can be incredibly strong, as you can see from the damage shown in Figure 1. During late summer and early fall, you have probably heard reports about severe storms known as hurricanes. Unlike tornadoes, hurricanes form over Earth's tropical oceans. As they move toward land, the strong winds and heavy rains produced by these storms can destroy anything in their paths. You are probably most familiar with a type of severe storm known as a thunderstorm. Thunderstorms are a type of severe weather that produces heavy rains, loud noises you know as thunder, and flashes of light called lightning. Before learning more about these different types of violent weather, you will learn about the atmospheric conditions that most often affect the day-to-day weather.

Air Masses and Weather

For the many people who live in the middle latitudes, which include much of the United States, summer heat waves and winter cold spells are familiar experiences. During summer heat waves, several days of high temperatures and high humidity often end when a series of storms pass through the area. This stormy weather is followed by a few days of relatively cool weather. By contrast, winter cold spells are often characterized by periods of frigid temperatures under clear skies. These bitter cold periods are usually followed by cloudy, snowy, relatively warm days that seem mild when compared to those just a day earlier. In both of these situations, periods of fairly constant weather conditions are followed by a short period of changes in the weather. What do you think causes these changes?

Air Masses The weather patterns just described result from movements of large bodies of air called air masses. **An air mass is an immense body of air that is characterized by similar temperatures and amounts of moisture at any given altitude.** An air mass can be 1600 kilometers or more across and several kilometers thick. Because of its size, it may take several days for an air mass to move over an area. This causes the area to experience fairly constant weather, a situation often called air-mass weather. Some day-to-day variations may occur, but the events will be very unlike those in an adjacent air mass.

Movement of Air Masses When an air mass moves out of the region over which it formed, it carries its temperature and moisture conditions with it. An example of the influence of a moving air mass is shown in Figure 2. A cold, dry air mass from northern Canada is shown moving southward. The initial temperature of the air mass is −46°C. It warms 13 degrees by the time it reaches Winnipeg. The air mass continues to warm as it moves southward through the Great Plains and into Mexico. Throughout its southward journey, the air mass becomes warmer. But it also brings some of the coldest weather of the winter to the places in its path. **As it moves, the characteristics of an air mass change and so does the weather in the area over which the air mass moves.**

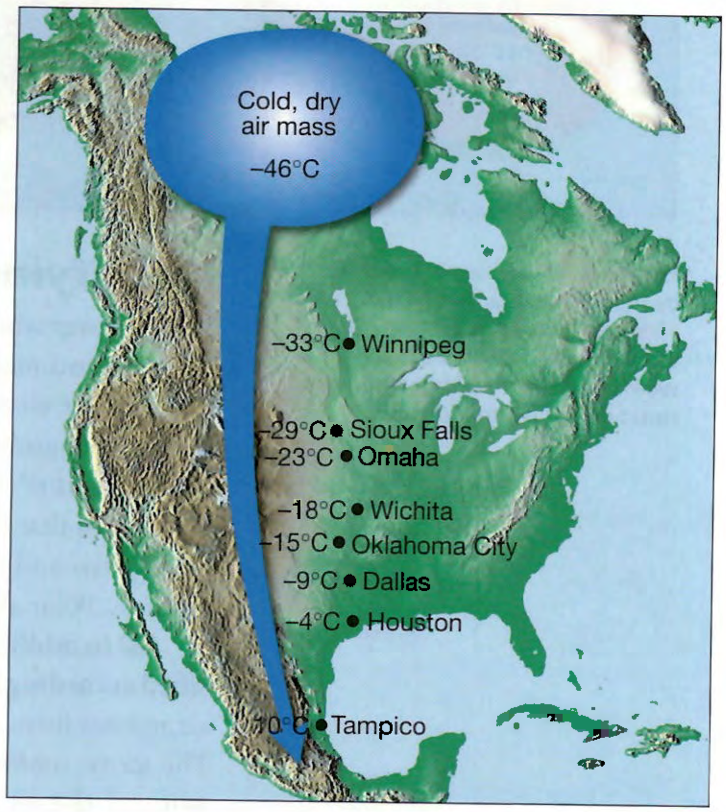

Figure 2 As a frigid Canadian air mass moves southward, it brings colder weather to the area over which it moves.
Computing ***How much warmer was the air mass when it reached Tampico, Mexico, than when it formed?***

Reading Checkpoint ***What is an air mass, and what happens as it moves over an area?***

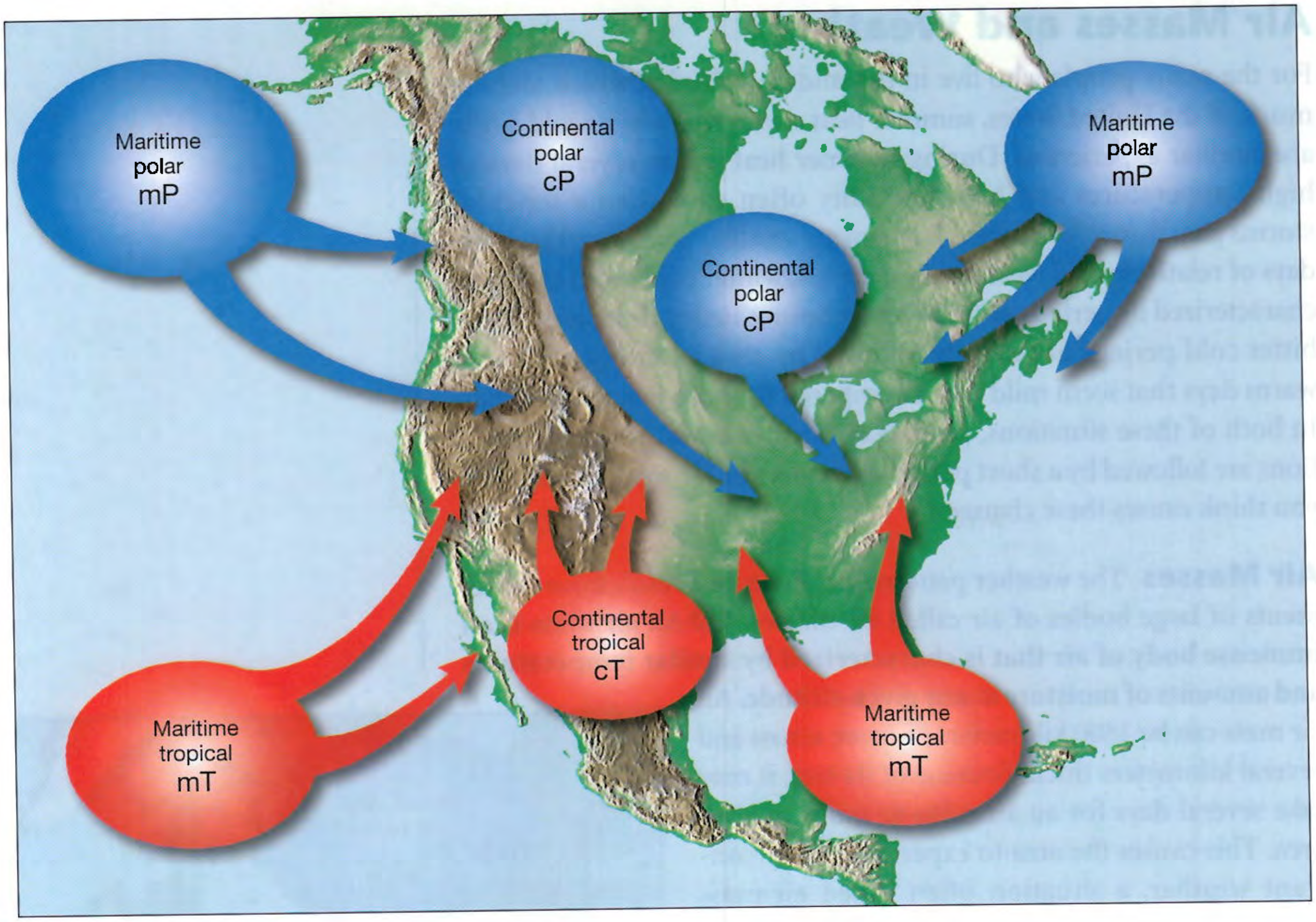

Figure 3 Air masses are classified by the region over which they form. **Interpreting Maps** ***What kinds of air masses influence the weather patterns along the west coast of the United States?***

Classifying Air Masses

The area over which an air mass gets its characteristic properties of temperature and moisture is called its source region. The source regions that produce air masses that influence the weather in North America are shown in Figure 3. Air masses are named according to their source region. Polar (P) air masses form at high latitudes toward Earth's poles. Air masses that form at low latitudes are tropical (T) air masses. The terms *polar* and *tropical* describe the temperature characteristics of an air mass. Polar air masses are cold, while tropical air masses are warm.

In addition to their overall temperature, air masses are classified according to the surface over which they form. Continental (c) air masses form over land. Maritime (m) air masses form over water. The terms *continental* and *maritime* describe the moisture characteristics of the air mass. Continental air masses are likely to be dry. Maritime air masses are humid.

Using this classification scheme, there are four basic types of air masses. A continental polar (cP) air mass is dry and cool. A continental tropical (cT) air mass is dry and warm or hot. Maritime polar (mP) and maritime tropical (mT) air masses both form over water. But a maritime polar air mass is much colder than a maritime tropical air mass.

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For: Links on air masses
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MAP MASTER™ Skills Activity

Figure 4

Location Marquette, Michigan, is southeast of Thunder Bay, Ontario.
Identify What type of air mass influences the weather of these two cities?
Infer Which of these cities receives more snow in an average winter? Why?

Weather in North America

Much of the weather in North America, especially weather east of the Rocky Mountains, is influenced by continental polar (cP) and maritime tropical (mT) air masses. The cP air masses begin in northern Canada, the interior of Alaska, and the Arctic areas. The mT air masses most often begin over the warm waters of the Gulf of Mexico, the Caribbean Sea, or the adjacent Atlantic Ocean.

Continental Polar Air Masses Continental polar air masses are uniformly cold and dry in winter and cool and dry in summer. In summer, cP air masses may bring a few days of relatively cooler weather. In winter, this continental polar air brings the clear skies and cold temperatures you associate with a cold wave.

Continental polar air masses are not, as a rule, associated with heavy precipitation. However, those that cross the Great Lakes during late autumn and winter sometimes bring snow to the leeward shores, as shown in Figure 4. These localized storms, which are known as lake-effect snows, make Buffalo and Rochester, New York, among the snowiest cities in the United States. What causes lake-effect snow? During late autumn and early winter, the difference in temperature between the lakes and adjacent land areas can be large. The temperature contrast can be especially great when a very cold cP air mass pushes southward across the lakes. When this occurs, the air gets large quantities of heat and moisture from the relatively warm lake surface. By the time it reaches the opposite shore, the air mass is humid and unstable. Heavy snow, like that shown in Figure 5, is possible.

Reading Checkpoint *What causes large amounts of snow to fall on the southern and eastern shores of the Great Lakes?*

Figure 5 A six-day lake-effect snowstorm in November 1996 dropped a record 175 cm (69 in.) of snow on Chardon, Ohio.

Figure 6 Rain Storm over Florida Bay in the Florida Keys

Maritime Tropical Air Masses Maritime tropical air masses also play a dominant role in the weather of North America. These air masses are warm, loaded with moisture, and usually unstable. Maritime tropical air is the source of much, if not most, of the precipitation received in the eastern two thirds of the United States. The heavy precipitation shown in Figure 6 is the result of maritime tropical air masses moving through the area. In summer, when an mT air mass invades the central and eastern United States, it brings the high temperatures and oppressive humidity typically associated with its source region.

Maritime Polar Air Masses During the winter, maritime polar air masses that affect weather in North America come from the North Pacific. Such air masses often begin as cP air masses in Siberia. The cold, dry continental polar air changes into relatively mild, humid, unstable maritime polar air during its long journey across the North Pacific, as shown in Figure 7. As this maritime polar air arrives at the western shore of North America, it is often accompanied by low clouds and showers. When this maritime polar air advances inland against the western mountains, uplift of the air produces heavy rain or snow on the windward slopes of the mountains.

Maritime polar air masses also originate in the North Atlantic off the coast of eastern Canada. These air masses influence the weather of the northeastern United States. In winter, when New England is on the northern or northwestern side of a passing low-pressure center, the counterclockwise winds draw in maritime polar air. The result is a storm characterized by snow and cold temperatures, known locally as a nor'easter.

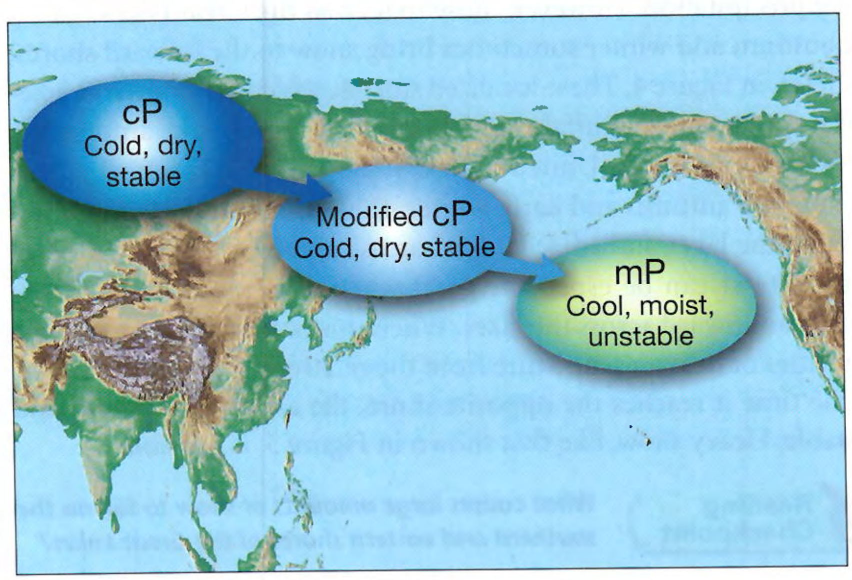


Figure 7 During winter, maritime polar (mP) air masses in the northern Pacific Ocean usually begin as continental polar (cP) air masses in Siberia. **Inferring** ***What happens to the mP air masses as they cross the Pacific?***

Continental Tropical Air Masses Continental tropical air masses have the least influence on the weather of North America. These hot, dry air masses begin in the southwestern United States and Mexico during the summer. **Only occasionally do cT air masses affect the weather outside their source regions.** However, when a cT air mass does move from its source region, it can cause extremely hot, droughtlike conditions in the Great Plains in the summer. Movement of such air masses in the fall results in mild weather in the Great Lakes region, often called Indian summer. Conditions during Indian summer are unseasonably warm and mild, as shown in Figure 8.

Figure 8 A cT air mass produces a few days of warm weather amid the cool days of fall in the Great Lakes region.

Section 20.1 Assessment

Reviewing Concepts

1. What is an air mass?
2. What happens as an air mass moves over an area?
3. How are air masses classified?
4. Which types of air masses have the greatest effect on weather in North America?
5. Why do continental tropical air masses have little effect on weather in North America?

Critical Thinking

6. **Comparing and Contrasting** Compare and contrast the four types of air masses.
7. **Explaining** Explain which type of air mass could offer relief from a scorching summer to the Midwestern United States. Justify your choice.
8. **Applying Concepts** How can continental polar air be responsible for lake-effect snowstorms in the Great Lakes region?
9. **Identifying** Look again at Figure 3. What kinds of air masses influence the weather patterns over Florida?
10. **Synthesizing** What kind of weather could be expected in southern Canada if an mT air mass was to invade the region in mid-July?

Writing in Science

Explanatory Paragraph Pick one of the air masses shown in Figure 3 that affects the weather in your area. Write a paragraph that explains the weather typically associated with the air mass in both the summer and the winter.

20.2 Fronts

Reading Focus

Key Concepts

- What happens when two air masses meet?
- How is a warm front produced?
- What is a cold front?
- What is a stationary front?
- What are the stages in the formation of an occluded front?
- What is a middle-latitude cyclone?
- What fuels a middle-latitude cyclone?

Vocabulary

- front
- warm front
- cold front
- stationary front
- occluded front

Reading Strategy

Outlining As you read, make an outline like the one below. Include information about how each of the weather fronts discussed in this section forms and the weather associated with each.

Fronts

I. Warm front

A. ____?____

B. ____?____

II. Cold front

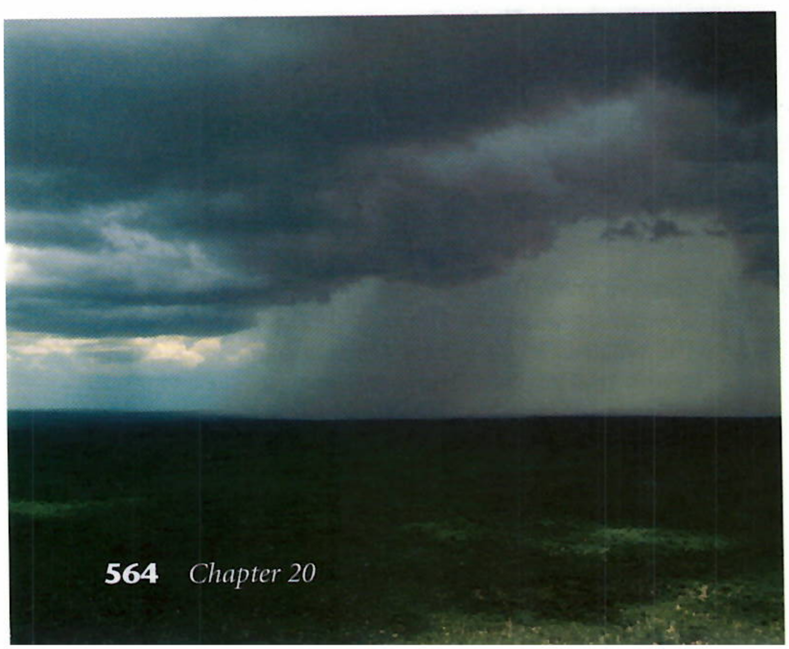
A. ____?____

B. ____?____

Formation of Fronts

Recall that air masses have different temperatures and amounts of moisture, depending on their source regions. Recall also that these properties can change as an air mass moves over a region. What do you think happens when two air masses meet? **When two air masses meet, they form a front, which is a boundary that separates two air masses.** Fronts can form between any two contrasting air masses. Fronts are often associated with some form of precipitation, such as that shown in Figure 9.

Figure 9 Precipitation from a Storm in South Africa



In contrast to the vast sizes of air masses, fronts are narrow. Most weather fronts are between about 15 and 200 km wide. Above Earth's surface, the frontal surface slopes at a low angle so that warmer, less dense air overlies cooler, denser air. In the ideal case, the air masses on both sides of a front move in the same direction and at the same speed. When this happens, the front acts simply as a barrier that travels with the air masses. In most cases, however, the distribution of pressure across a front causes one air mass to move faster than the other. When this happens, one air mass advances into another, and some mixing of air occurs.

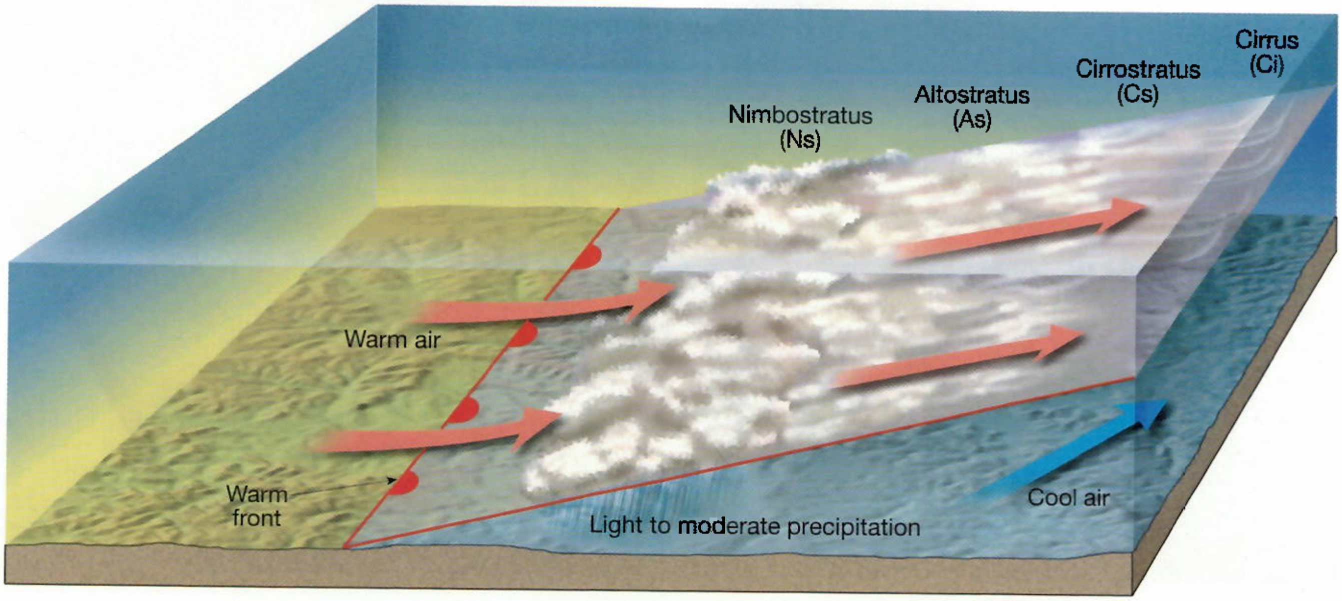


Figure 10 Formation of a Warm Front A warm front forms when warm air glides up over a cold, dense air mass. The affected area has warmer temperatures, and light to moderate precipitation.

Types of Fronts

Fronts are often classified according to the temperature of the advancing front. There are four types of fronts: warm fronts, cold fronts, stationary fronts, and occluded fronts.

Warm Fronts

A warm front forms when warm air moves into an area formerly covered by cooler air. On a weather map, the surface position of a warm front is shown by a red line with red semicircles that point toward the cooler air.

The slope of the warm front is very gradual, as shown in Figure 10. As warm air rises, it cools to produce clouds, and frequently precipitation. The sequence of clouds shown in Figure 10 typically comes before a warm front. The first sign of the approaching warm front is the appearance of cirrus clouds. As the front nears, cirrus clouds change into cirrostratus clouds, which blend into denser sheets of altostratus clouds. About 300 kilometers ahead of the front, thicker stratus and nimbostratus clouds appear, and rain or snow begins.

Because of their slow rate of movement and very low slope, warm fronts usually produce light-to-moderate precipitation over a large area for an extended period. A gradual increase in temperature occurs with the passage of a warm front. The increase is most apparent when a large temperature difference exists between adjacent air masses. Also, a wind shift from the east to the southwest is associated with a warm front.

Reading Checkpoint ***What causes a warm front to form?***

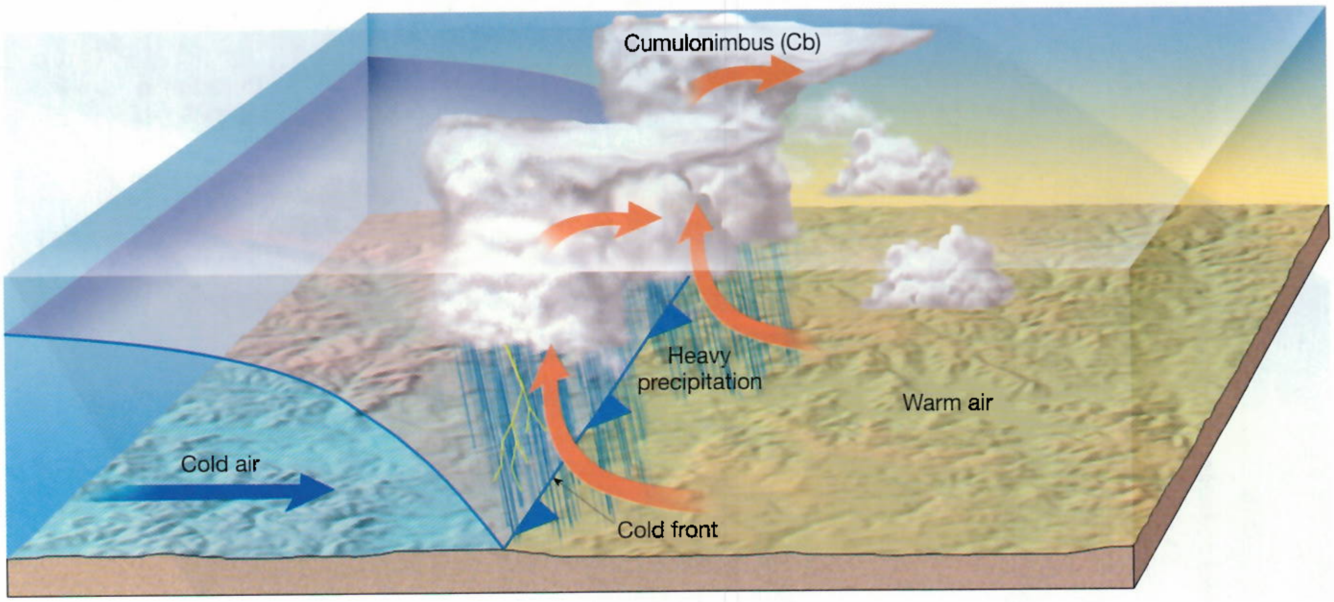


Figure 11 Formation of a Cold Front A cold front forms when cold air moves into an area occupied by warmer air. The affected area experiences thunderstorms if the warm air is unstable.

Cold Fronts **A cold front forms when cold, dense air moves into a region occupied by warmer air.** On a weather map, the surface position of a cold front is shown by a blue line edged with blue triangles that point toward the warmer air mass.

Figure 11 shows how a cold front develops. As this cold front moves, it becomes steeper. On average, cold fronts are about twice as steep as warm fronts and advance more rapidly than warm fronts do. These two differences—rate of movement and steepness of slope—account for the more violent weather associated with a cold front.

The forceful lifting of air along a cold front can lead to heavy downpours and gusty winds. As a cold front approaches, towering clouds often can be seen in the distance. Once the cold front has passed, temperatures drop and wind shifts. The weather behind a cold front is dominated by a cold air mass. So, weather clears soon after a cold front passes. When a cold front moves over a warm area, low cumulus or stratocumulus clouds may form behind the front.

Stationary Fronts Occasionally, the flow of air on either side of a front is neither toward the cold air mass nor toward the warm air mass, but almost parallel to the line of the front. **In such cases, the surface position of the front does not move, and a stationary front forms.** On a weather map, stationary fronts are shown by blue triangles on one side of the front and red semicircles on the other. Sometimes, gentle to moderate precipitation occurs along a stationary front.

Reading Checkpoint ***How are cold fronts different from warm fronts?***

Occluded Fronts **When an active cold front overtakes a warm front, an occluded front forms.** As you can see in Figure 12, an occluded front develops as the advancing cold air wedges the warm front upward. The weather associated with an occluded front is generally complex. Most precipitation is associated with the warm air's being forced upward. When conditions are suitable, however, the newly formed front is capable of making light precipitation of its own.

It is important to note that the descriptions of weather associated with fronts are general descriptions. The weather along any individual front may or may not conform to the idealized descriptions you've read about. Fronts, like all aspects of nature, do not always behave as we would expect.

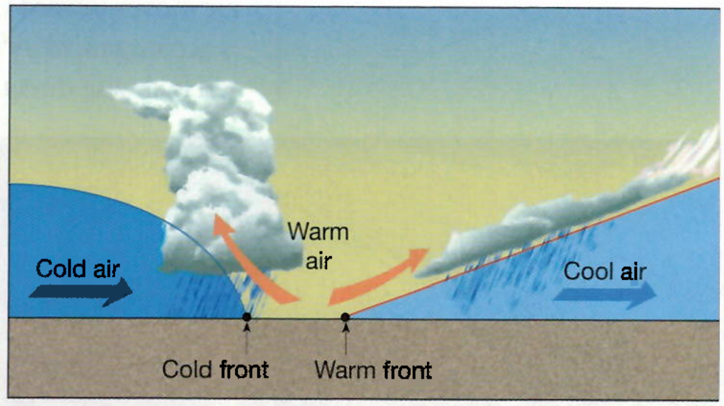
Middle-Latitude Cyclones

Now that you know about air masses and what happens when they meet, you're ready to apply this information to understanding weather patterns in the United States. The main weather producers in the country are middle-latitude cyclones. On weather maps, these low-pressure areas are shown by the letter L.

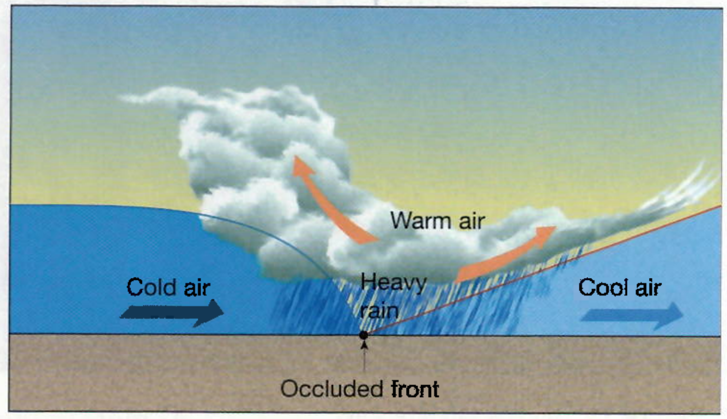
Middle-latitude cyclones are large centers of low pressure that generally travel from west to east and cause stormy weather. The air in these weather systems moves in a counterclockwise direction and in toward the center of the low. Most middle-latitude cyclones have a cold front, and frequently a warm front, extending from the central area. Forceful lifting causes the formation of clouds that drop abundant precipitation.

How do cyclones develop and form? The first stage is the development of a front, which is shown in Figure 14A on page 569. The front forms as two air masses with different temperatures move in opposite directions. Over time, the front takes on a wave shape, as shown in Figure 14B. The wave is usually hundreds of kilometers long.

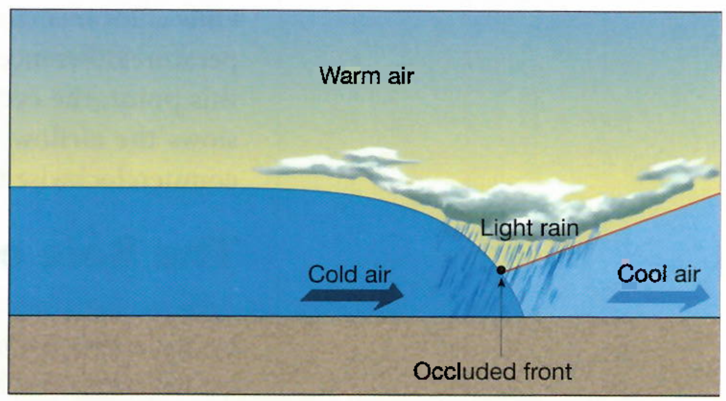
Formation of an Occluded Front



A A cold front moves toward a warm front, forcing warm air aloft.



B A cold front merges with the warm front to form an occluded front that drops heavy rains.



C Because occluded fronts often move slowly, light precipitation can fall for several days.

Figure 12 An occluded front forms when a cold front overtakes a warm front, producing a complex weather pattern.

As the wave develops, warm air moves towards Earth's poles. There it invades the area formerly occupied by colder air. Meanwhile, cold air moves toward the equator. This change in airflow near the surface is accompanied by a change in pressure. The result is airflow in a counterclockwise direction, as Figure 14C shows.

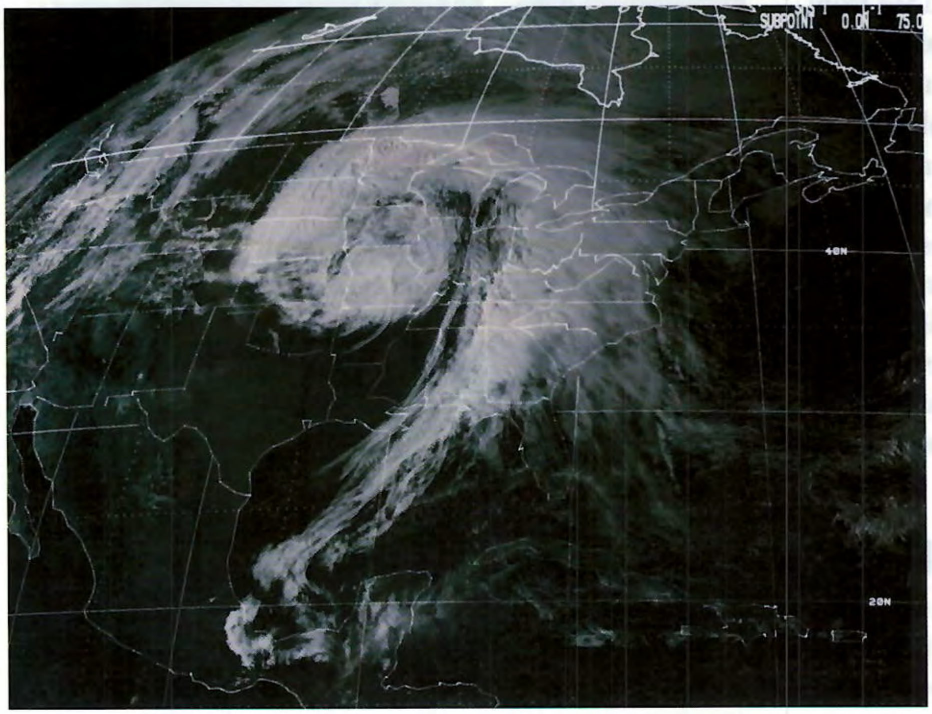


Figure 13 This is a satellite view of a mature cyclone over the eastern United States.

Recall that a cold front advances faster than a warm front. When this occurs in the development of a middle-latitude cyclone, the cold front closes in and eventually lifts the warm front, as Figure 14D shows. This process, which is known as occlusion, forms the occluded front shown in Figure 14E. As occlusion begins, the storm often gets stronger. Pressure at the storm's center falls, and wind speeds increase. In the winter, heavy snowfalls and blizzard-like conditions are possible during this phase of the storm's evolution. A satellite view of this phase of a mature cyclone is shown in Figure 13.

As more of the warm air is forced to rise, the amount of pressure change weakens. In a day or two, the entire warm area is displaced. Only cold air surrounds the cyclone at low levels. The horizontal temperature difference that existed between the two air masses is gone. At this point, the cyclone has exhausted its source of energy. Friction slows the airflow near the surface, and the once highly organized counterclockwise flow ceases to exist (Figure 14F).

The Role of Airflow Aloft

Airflow aloft plays an important role in maintaining cyclonic and anticyclonic circulation. In fact, these rotating surface wind systems are actually generated by upper-level flow.

Cyclones often exist for a week or longer. For this to happen, surface convergence must be offset by outflow somewhere higher in the atmosphere. As long as the spreading out of air high up is equal to or greater than the surface inflow, the low-pressure system can be sustained. **More often than not, air high up in the atmosphere fuels a middle-latitude cyclone.**

Reading Checkpoint ***How do middle-latitude cyclones form and develop?***

Middle-Latitude Cyclone Model

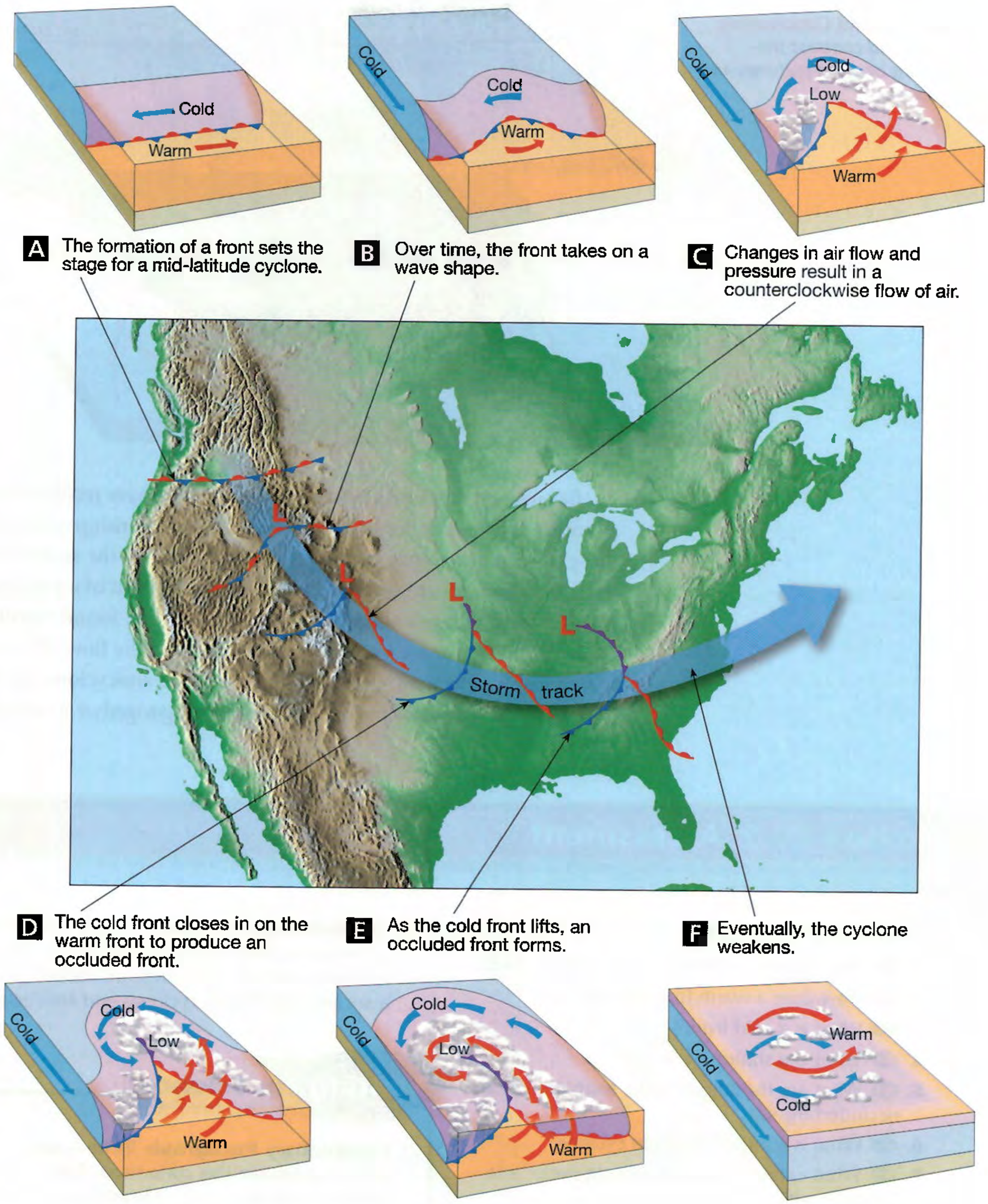


Figure 14 Cyclones have a fairly predictable life cycle.

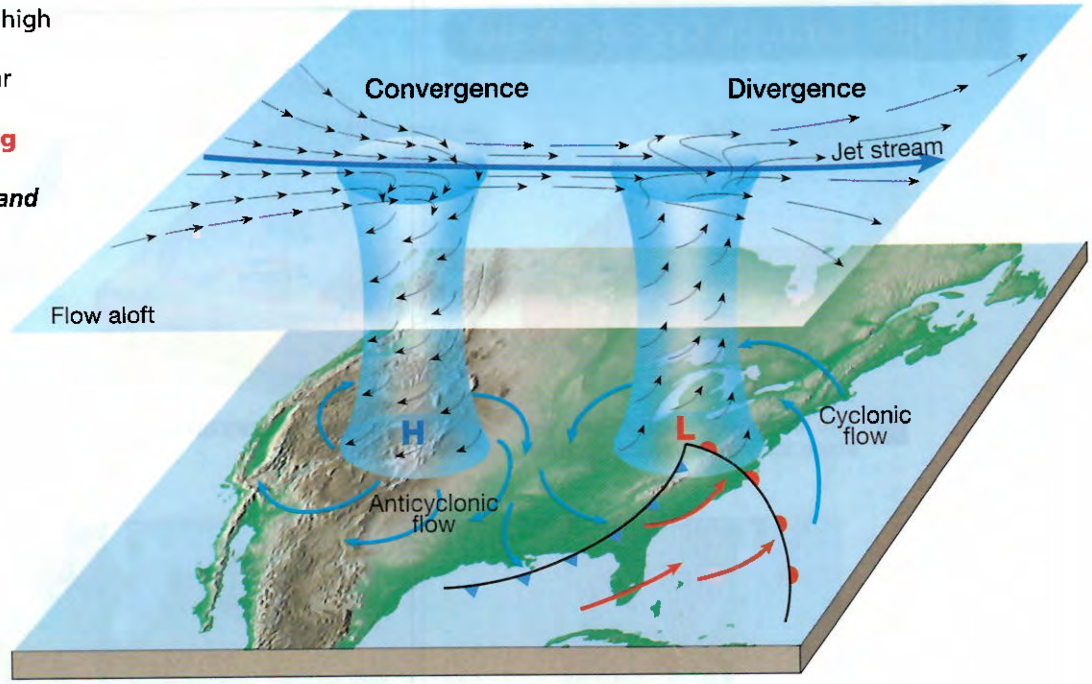


Figure 15 Movements of air high in the atmosphere fuel the cyclones and anticyclones near Earth's surface.
Comparing and Contrasting ***Compare and contrast the movement of air in cyclones and anticyclones.***

Because cyclones bring stormy weather, they have received far more attention than anticyclones. However, a close relationship exists between these two pressure systems. As shown in Figure 15, the surface air that feeds a cyclone generally originates as air flowing out of an anticyclone. As a result, cyclones and anticyclones typically are found next to each other. Like a cyclone, an anticyclone depends on the flow of air high in the atmosphere to maintain its circulation. In an anticyclone, air spreading out at the surface is balanced by air coming together from high up.

Section 20.2 Assessment

Reviewing Concepts

1. What happens when two air masses meet?
2. How does a warm front form?
3. What is a cold front?
4. What is a stationary front?
5. What are the stages in the formation of an occluded front?
6. What is a middle-latitude cyclone?
7. What causes a middle-latitude cyclone to sustain itself?

Critical Thinking

8. **Comparing and Contrasting** Compare and contrast warm fronts and cold fronts.
9. **Synthesizing** Use Figure 15 and what you know about Earth's atmosphere to describe the air movement and pressure conditions associated with both cyclones and anticyclones.

Writing in Science

Explanatory Paragraph Write a paragraph to explain this statement: The formation of an occluded front marks the beginning of the end of a middle-latitude cyclone.

20.3 Severe Storms

Reading Focus

Key Concepts

- What is a thunderstorm?
- What causes a thunderstorm to form?
- What is a tornado?
- How does a tornado form?
- What is a hurricane?
- How does a hurricane form?

Vocabulary

- thunderstorm
- tornado
- hurricane
- eye wall
- eye
- storm surge

Reading Strategy

Identifying Cause and Effect Copy the table and complete it as you read this section.

Severe Storms		
	Causes	Effects
Thunderstorms	a. ___?___	b. ___?___
Tornadoes	c. ___?___	d. ___?___
Hurricanes	e. ___?___	f. ___?___

Severe weather has a fascination that everyday weather does not provide. For example, a thunderstorm with its jagged lightning and booming thunder can be an awesome sight. The damage and destruction caused by these storms, as well as other severe weather, can also be frightening. A single severe storm can cause billions of dollars in property damage as well as many deaths. This section discusses three types of severe storms and their causes.

Thunderstorms

Have you ever seen a small whirlwind carry dust or leaves upward on a hot day? Have you observed a bird glide effortlessly skyward on an invisible updraft of hot air? If so, you have observed the effects of the vertical movements of relatively warm, unstable air. These examples are caused by a similar thermal instability that occurs during the development of a thunderstorm. **A thunderstorm is a storm that generates lightning and thunder. Thunderstorms frequently produce gusty winds, heavy rain, and hail.** A thunderstorm may be produced by a single cumulonimbus cloud and influence only a small area. Or it may be associated with clusters of cumulonimbus clouds that stretch for kilometers along a cold front.

Figure 16 Lightning is a spectacular and potentially dangerous feature of a thunderstorm.

Stages in the Development of a Thunderstorm

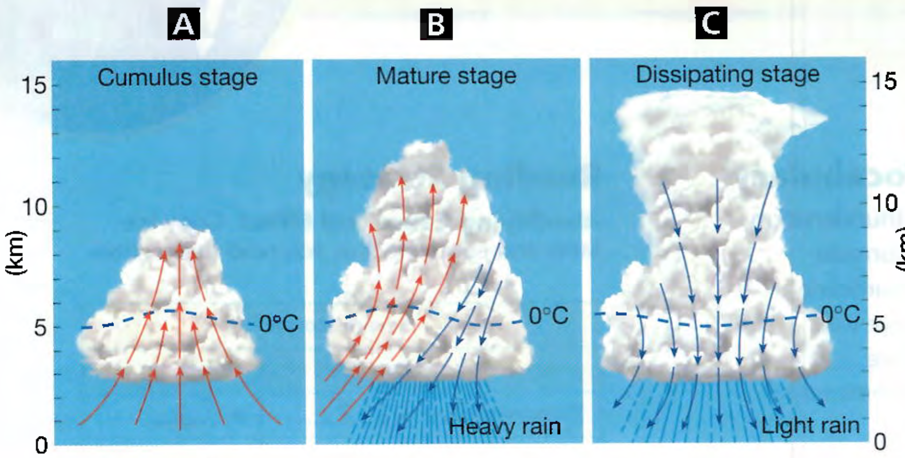


Figure 17 **A** During the cumulus stage, warm, moist air is supplied to the cloud. **B** Heavy precipitation falls during the mature stage. **C** The cloud begins to evaporate during the dissipating stage. **Observing** ***How do the clouds involved in the development of a thunderstorm vary?***

Occurrence of Thunderstorms How common are thunderstorms? Consider these numbers. At any given time, there are an estimated 2000 thunderstorms in progress on Earth. As you might expect, the greatest number occurs in the tropics where warmth, plentiful moisture, and instability are common atmospheric conditions. About 45,000 thunderstorms take place each day. More than 16 million occur annually around the world. The United States experiences about 100,000 thunderstorms each year, most frequently in Florida and the eastern Gulf Coast region. Most parts of the country have from 30 to 100 storms each year. The western margin of the United States has little thunderstorm activity because warm, moist, unstable maritime tropical air seldom penetrates this region.

Development of Thunderstorms **Thunderstorms form when warm, humid air rises in an unstable environment.** The development of a thunderstorm generally involves three stages. During the cumulus stage, shown in Figure 17A, strong updrafts, or upward movements of air, supply moist air. Each new surge of warm air rises higher than the last and causes the cloud to grow vertically.

Usually within an hour of the initial updraft, the mature stage begins, as shown in Figure 17B. At this point in the development of the thunderstorm, the amount and size of the precipitation is too great for the updrafts to support. So, heavy precipitation is released from the cloud. The mature stage is the most active stage of a thunderstorm. Gusty winds, lightning, heavy precipitation, and sometimes hail are produced during this stage.

Eventually, downdrafts, or downward movements of air, dominate throughout the cloud, as shown in Figure 17C. This final stage is called the dissipating stage. During this stage, the cooling effect of the falling precipitation and the flowing in of colder air from high above cause the storm to die down.

The life span of a single cumulonimbus cell within a thunderstorm is only about an hour or two. As the storm moves, however, fresh supplies of warm, humid air generate new cells to replace those that are scattering.

Reading Checkpoint ***Describe the stages in the development of a thunderstorm.***

Tornadoes

Tornadoes are violent windstorms that take the form of a rotating column of air called a vortex. The vortex extends downward from a cumulonimbus cloud. Some tornadoes consist of a single vortex. But within many stronger tornadoes, smaller vortexes rotate within the main funnel. These smaller vortexes have diameters of only about 10 meters and rotate very rapidly. Smaller vortexes explain occasional observations of tornado damage in which one building is totally destroyed, while another one, just 10 or 20 meters away, suffers little damage.

Occurrence and Development of Tornadoes In the United States, about 770 tornadoes are reported each year. These severe storms can occur at any time during the year. However, the frequency of tornadoes is greatest from April through June. In December and January, tornadoes are far less frequent.

Most tornadoes form in association with severe thunderstorms. An important process in the formation of many tornadoes is the development of a mesocyclone. A mesocyclone is a vertical cylinder of rotating air that develops in the updraft of a thunderstorm. The formation of this large vortex begins as strong winds high up in the atmosphere cause winds lower in the atmosphere to roll, as shown in Figure 18A. In Figure 18B, you can see that strong thunderstorm updrafts cause this rolling air to tilt. Once the air is completely vertical (Figure 18C), the mesocyclone is well established. The formation of a mesocyclone does not necessarily mean that a tornado will follow. Few mesocyclones produce tornadoes like the one shown in Figure 19 on page 574.

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Q & A

Q *What is the most destructive tornado on record?*

A The Tri-State Tornado, which occurred on March 18, 1925, started in southeastern Missouri and remained on the ground over a distance of 352 kilometers, until it reached Indiana. Casualties included 695 people dead and 2027 injured. Property losses were also great, with several small towns almost totally destroyed.

Formation of a Mesocyclone

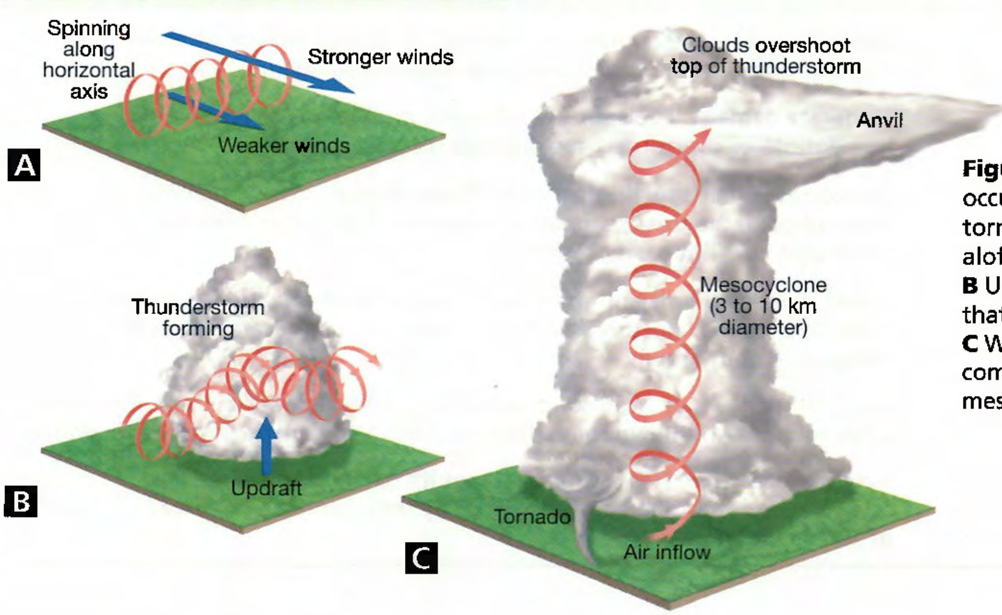


Figure 18 A mesocyclone can occur before the formation of a tornado. **A** First, stronger winds aloft cause lower winds to roll. **B** Updrafts tilt the rolling air so that it becomes nearly vertical. **C** When the rotating air is completely vertical, the mesocyclone is established.

Figure 19 The tornado shown here descended from the lower portion of a mesocyclone in the Texas Panhandle in May, 1996.

Tornado Intensity Pressures within some tornadoes have been estimated to be as much as 10 percent lower than pressures immediately outside the storm. The low pressure within a tornado causes air near the ground to rush into a tornado from all directions. As the air streams inward, it spirals upward around the core. Eventually, the air merges with the airflow of the cumulonimbus cloud that formed the storm. Because of the tremendous amount of pressure change associated with a strong tornado, maximum winds can sometimes approach 480 kilometers per hour. One scale used to estimate tornado intensity is the Fujita tornado intensity scale, shown in Table 1. Because tornado winds cannot be measured directly, a rating on this scale is determined by assessing the worst damage produced by a storm.

Tornado Safety The Storm Prediction Center (SPC) located in Norman, Oklahoma, monitors different kinds of severe weather. The SPC's mission is to provide timely and accurate forecasts and watches for severe thunderstorms and tornadoes. Tornado watches alert people to the possibility of tornadoes in a specified area for a particular time period. A tornado warning is issued when a tornado has actually been sighted in an area or is indicated by weather radar.

Table 1 Fujita Tornado Intensity Scale

Intensity	Wind Speed Estimates (kph)	Typical Damage
F0	< 116	Light damage. Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.
F1	116–180	Moderate damage. Peels surface off roofs; mobile homes pushed off foundations or overturned; moving cars blown off roads.
F2	181–253	Considerable damage. Roofs torn off frame houses; mobile homes demolished; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.
F3	254–332	Severe damage. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.
F4	333–419	Devastating damage. Well-constructed houses leveled; structures with weak foundations blown some distance; cars thrown; large missiles generated.
F5	> 419	Incredible damage. Strong frame houses lifted off foundations and carried away; automobile-sized missiles fly through the air in excess of 100 m; bark torn off trees.

Hurricanes

If you've ever been to the tropics or seen photographs of these regions, you know that warm breezes, steady temperatures, and heavy but brief tropical showers are the norm. It is ironic that these tranquil regions sometimes produce the most violent storms on Earth. **Whirling tropical cyclones that produce winds of at least 119 kilometers per hour are known in the United States as hurricanes.** In other parts of the world, these severe tropical storms are called typhoons, cyclones, and tropical cyclones.

Regardless of the name used to describe them, hurricanes are the most powerful storms on Earth. At sea, they can generate 15-meter waves capable of destruction hundreds of kilometers away. Should a hurricane hit land, strong winds and extensive flooding can cause billions of dollars in damage and great loss of life. Hurricane Floyd, which is shown in a satellite image in Figure 20, was one such storm. In September 1999, Floyd brought flooding rains, high winds, and rough seas to a large portion of the Atlantic coast. More than 2.5 million people evacuated their homes. Torrential rains caused devastating inland flooding. Floyd was the deadliest hurricane to strike the U.S. mainland since Hurricane Agnes in 1972. Most of the deaths caused by Hurricane Floyd were the result of drowning from floods.

Hurricanes are becoming a growing threat because more and more people are living and working near coasts. At the close of the twentieth century, more than 50 percent of the U.S. population lived within 75 kilometers of a coast. This number is expected to increase even more in the early decades of this century. High population density near shorelines means that hurricanes and other large storms place millions of people at risk.

Q & A

Q *Why are hurricanes given names, and who picks the names?*

A Actually, the names are given once the storms reach tropical-storm status (winds between 61–119 kilometers per hour). Tropical storms are named to provide ease of communication between forecasters and the general public regarding forecasts, watches, and warnings. Tropical storms and hurricanes can last a week or longer, and two or more storms can be occurring in the same region at the same time. Thus, names can reduce the confusion about what storm is being described.

The World Meteorological Organization creates the lists of names. The names for Atlantic storms are used again at the end of a six-year cycle unless a hurricane was particularly destructive or otherwise noteworthy. Such names are retired to prevent confusion when the storms are discussed in future years.

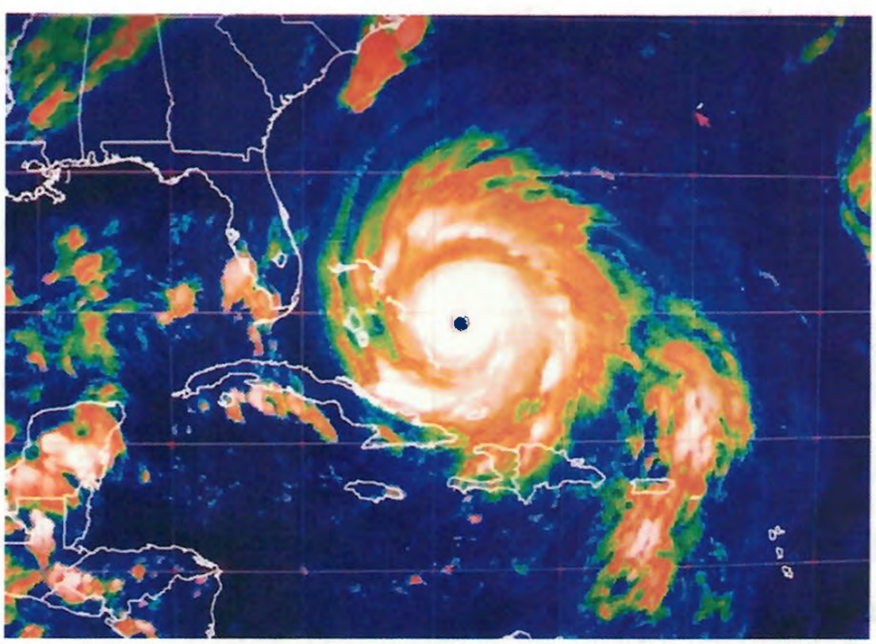


Figure 20 This satellite image of Hurricane Floyd shows its position off the coast of Florida a few days before the hurricane moved onto land. Floyd eventually made landfall near Cape Fear, North Carolina.

Occurrence of Hurricanes Most hurricanes form between about 5 and 20 degrees north and south latitude. The North Pacific has the greatest number of storms, averaging 20 per year. The coastal regions of the southern and eastern United States experience fewer than five hurricanes, on average, per year. Although many tropical disturbances develop each year, only a few reach hurricane status. A storm is a hurricane if the spiraling air has winds blowing at speeds of at least 119 kilometers per hour.

Development of Hurricanes A hurricane is a heat engine that is fueled by the energy given off when huge quantities of water vapor condense. **Hurricanes develop most often in the late summer when water temperatures are warm enough to provide the necessary heat and moisture to the air.** A hurricane begins as a tropical disturbance that consists of disorganized clouds and thunderstorms. Low pressures and little or no rotation are characteristic of these storms.

Occasionally, tropical disturbances become hurricanes. Figure 21 shows a cross section of a well-developed hurricane. An inward rush of warm, moist surface air moves toward the core of the storm. The air then turns upward and rises in a ring of cumulonimbus clouds. This doughnut-shaped wall that surrounds the center of the storm is the **eye wall.** Here the greatest wind speeds and heaviest rainfall occur. Surrounding the eye wall are curved bands of clouds that trail away from the center of the storm. Notice that near the top of the hurricane, the rising air is carried away from the storm center. This outflow provides room for more inward flow at the surface.

At the very center of the storm is the **eye** of the hurricane. This well-known feature is a zone where precipitation ceases and winds subside. The air within the eye gradually descends and heats by compression, making it the warmest part of the storm.

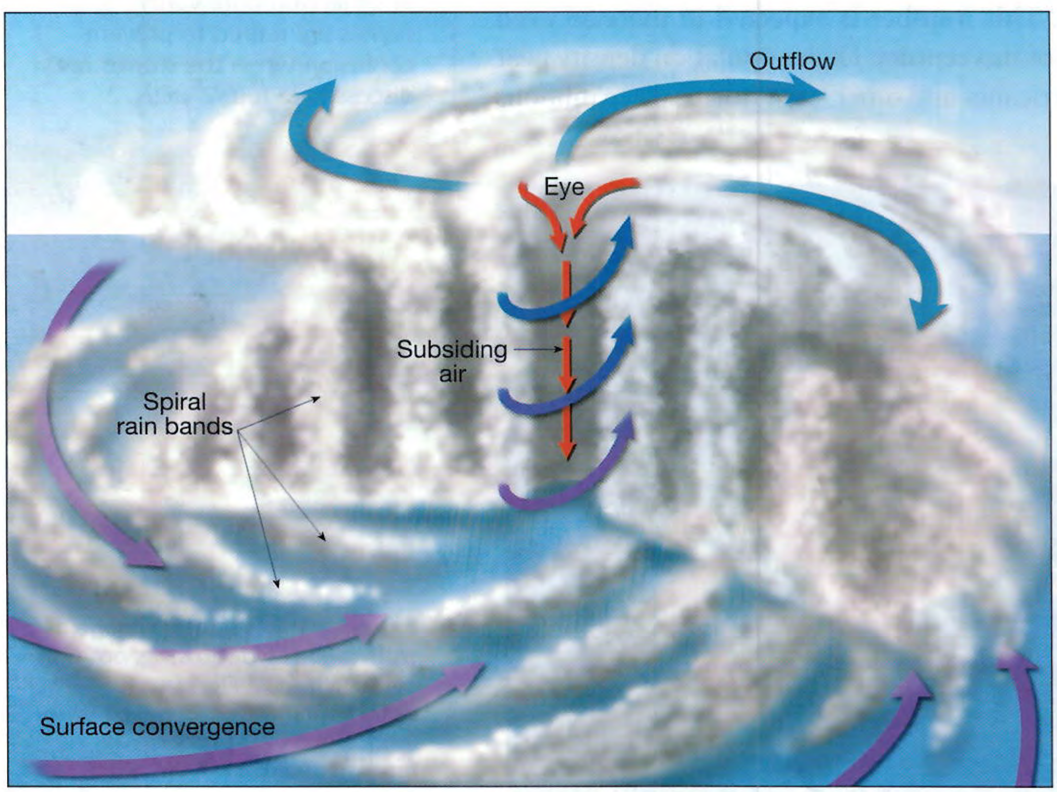


Figure 21 Cross Section of a Hurricane The eye of the hurricane is a zone of relative calm, unlike the eye wall region where winds and rain are most intense.
Describing ***Describe the airflow in different parts of a hurricane.***

Hurricane Intensity The intensity of a hurricane is described using the Saffir-Simpson scale shown in Table 2. The most devastating damage from a hurricane is caused by storm surges. A **storm surge** is a dome of water about 65 to 80 kilometers wide that sweeps across the coast where a hurricane's eye moves onto land.

A hurricane weakens when it moves over cool ocean waters that cannot supply adequate heat and moisture. Intensity also drops when storms move over land because there is not sufficient moisture. In addition, friction with the rough land surface causes winds to subside. Finally, if a hurricane reaches a location where the airflow aloft is unfavorable, it will die out.

Table 2 Saffir-Simpson Hurricane Scale

Category	Sustained Wind Speeds (kph)	Typical Damage
1	119–153	Storm surge 1.2–1.5 meters; some damage to unanchored mobile homes, shrubbery, and trees; some coastal flooding; minor pier damage.
2	154–177	Storm surge 1.6–2.4 meters; some damage to buildings' roofs, doors, and windows; considerable damage to mobile homes and piers; moderate coastal flooding.
3	178–209	Storm surge 2.5–3.6 meters; some structural damage to small buildings; some large trees blown over; mobile homes destroyed; some coastal and inland flooding.
4	210–249	Storm surge 3.7–5.4 meters; severe damage to trees and signs; complete destruction of mobile homes; extensive damage to doors and windows; severe flooding inland.
5	> 249	Storm surge >5.4 meters; complete roof failure on many buildings; some complete building failure; all trees and signs blown away; major inland flooding.

Section 20.3 Assessment

Reviewing Concepts

1. What is a thunderstorm?
2. What causes a thunderstorm?
3. What is a tornado?
4. How does a tornado form?
5. What is a hurricane?
6. How does a hurricane form?

Critical Thinking

7. **Formulating Hypotheses** What kind of front is associated with the formation of tornadoes? Explain.
8. **Synthesizing** Explain why a hurricane quickly loses its strength as the storm moves onto land.

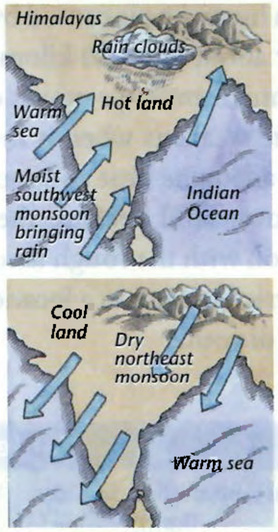
Writing in Science

Explanatory Paragraph Examine Tables 1 and 2 to contrast the damage caused by tornadoes and hurricanes. Use the data to explain why even though hurricanes have lower wind speeds, they often cause more damage than tornadoes do.

How the Earth Works

Winds and Storms

The world's atmosphere is forever on the move. **Wind,** or air in motion, occurs because solar radiation heats up some parts of the sea and land more than others. Air above these hot spots becomes warmer and lighter than the surrounding air and therefore rises. Elsewhere, cool air sinks because it is heavier. Winds blow because air squeezed out by sinking, cold air is sucked in under rising, warm air. Wind may move slowly as in a gentle breeze. In extreme weather, wind moves rapidly, creating terrifyingly destructive storms.



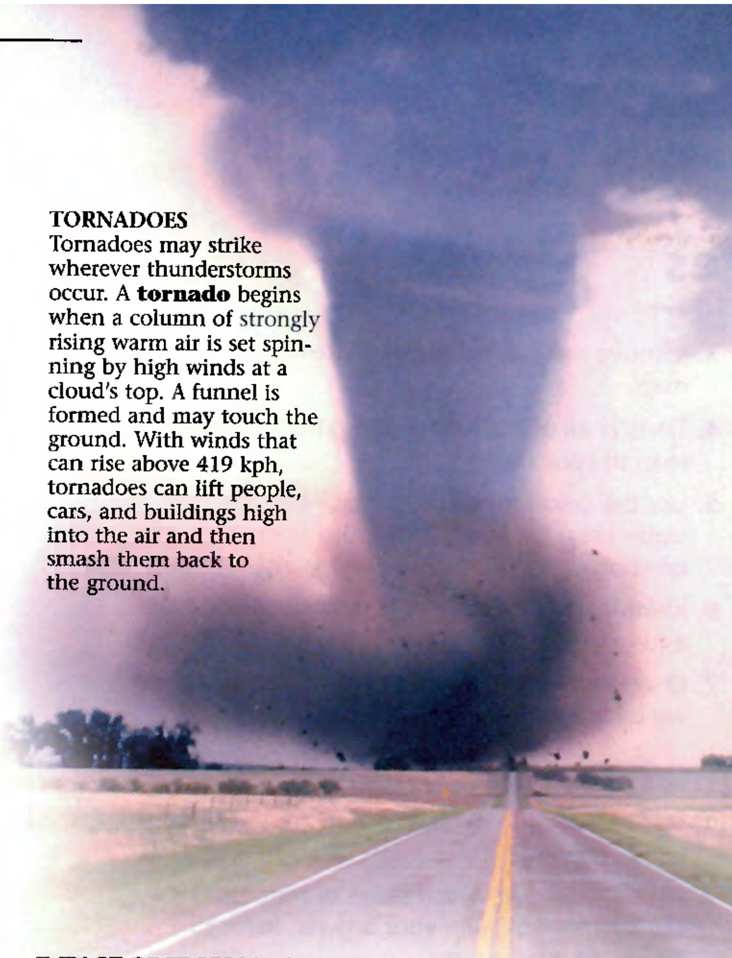
Southwest Monsoon *During the early summer, the hot, dry lands of Asia draw in cooler, moist air from the Indian Ocean.*

Northeast Monsoon *The cold, dry winter air from Central Asia brings chilly, dusty conditions to South Asia.*

MONSOONS
Seasonal winds called monsoons affect large areas of the tropics and subtropics. They occur in South Asia, southern North America, eastern Australia, and other regions of the world. In South Asia, southwest monsoons generally bring desperately needed rain from May until October.

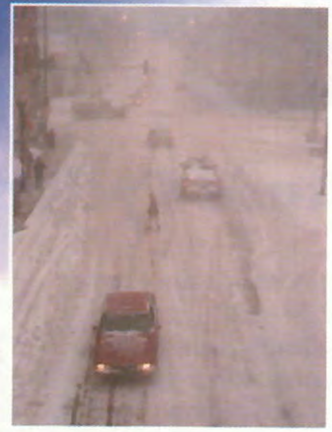
THUNDERSTORMS
Thunderclouds are formed by powerful updrafts of air that occur along cold fronts or over ground heated very strongly by the sun. Ice crystals and water droplets high in the cloud are torn apart and smashed together with such ferocity that they become charged with electricity. Thunderstorms can unleash thunder, lightning, wind, rain, and hail.

LIGHTNING AND THUNDER
Electricity is discharged from a thundercloud in the form of lightning. A bolt of lightning can heat the air around it to a temperature four times as hot as the sun. The heated air expands violently and sends out a rumbling shock wave that we hear as thunder.



TORNADOES

Tornadoes may strike wherever thunderstorms occur. A **tornado** begins when a column of strongly rising warm air is set spinning by high winds at a cloud's top. A funnel is formed and may touch the ground. With winds that can rise above 419 kph, tornadoes can lift people, cars, and buildings high into the air and then smash them back to the ground.



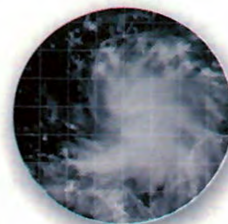
BLIZZARDS

In a **blizzard,** heavy snowfall and strong winds often make it impossible to see. Winds pile up huge drifts of snow. Travel and communication can grind to a halt.

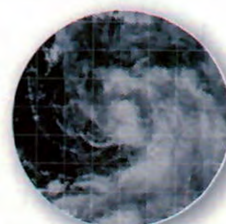
HOW TROPICAL STORMS DEVELOP

Tropical storms begin when water evaporates over an ocean in a hot tropical region to produce huge clouds and thunderstorms. When the storms cluster together and whirl around a low-pressure center, they form a **tropical cyclone.** Tropical cyclones with winds of at least 119 kph are called hurricanes in some regions and **typhoons** in other regions. The sequence below shows satellite images of an Atlantic hurricane.

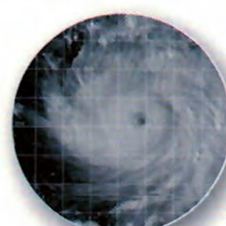
Stage 1: Thunderstorms develop over the ocean.



Stage 2: Storms group to form a swirl of cloud.



Stage 3: Winds grow and a distinct center forms in the cloud swirl.



Stage 4: Eye forms. The hurricane is now at its most dangerous.

Stage 5: Eye passes over land. The hurricane starts to weaken.

IMPACT OF TROPICAL STORMS

Tropical storms are often devastating. The strongest winds, with gusts sometimes more than 249 kph, occur at the storm's center, or eye. When a tropical storm strikes land, raging winds can uproot trees and destroy buildings. Vast areas may be swamped by torrential rain, and coastal regions may be overwhelmed by a **storm surge,** a wall of water some 8 m high sucked up by the storm's eye.

These women wade through the streets of Dhaka, Bangladesh, flooded by a tropical cyclone. In 1991, a cyclone killed more than 130,000 Bangladeshis.

A Pacific typhoon struck this ship off the coast of Taiwan in November 2000. Many of the crew members fell victim to the raging sea.

ASSESSMENT

1. **Key Terms** Define **(a)** wind, **(b)** tornado, **(c)** blizzard, **(d)** tropical cyclone, **(e)** typhoon, **(f)** storm surge.
2. **Physical Processes** How do thunderstorms come into being?
3. **Economic Activities** **(a)** How can storms have a negative impact on economic activities? **(b)** How can monsoons benefit economic activities?
4. **Natural Hazards** How can a tropical cyclone result in the loss of thousands of lives?
5. **Critical Thinking** **Developing a Hypothesis** Since 1991, the Bangladeshi government has constructed hundreds of concrete storm shelters in coastal regions of the country. **(a)** Why do you think the government decided on this policy? **(b)** How do you think the policy has benefited the country?

Application Lab

Middle-Latitude Cyclones

You've learned that much of the day-to-day weather in the United States is caused by middle-latitude cyclones. In this lab, you will identify some of the atmospheric conditions associated with a middle-latitude cyclone. Then you will use what you know about Earth's atmosphere and weather to predict how the movement of the low-pressure system affects weather in the area.

Problem How do middle-latitude cyclones affect weather patterns?

Materials

- tracing paper
- sharp pencil
- paper clips or removable tape
- metric ruler
- colored pencils

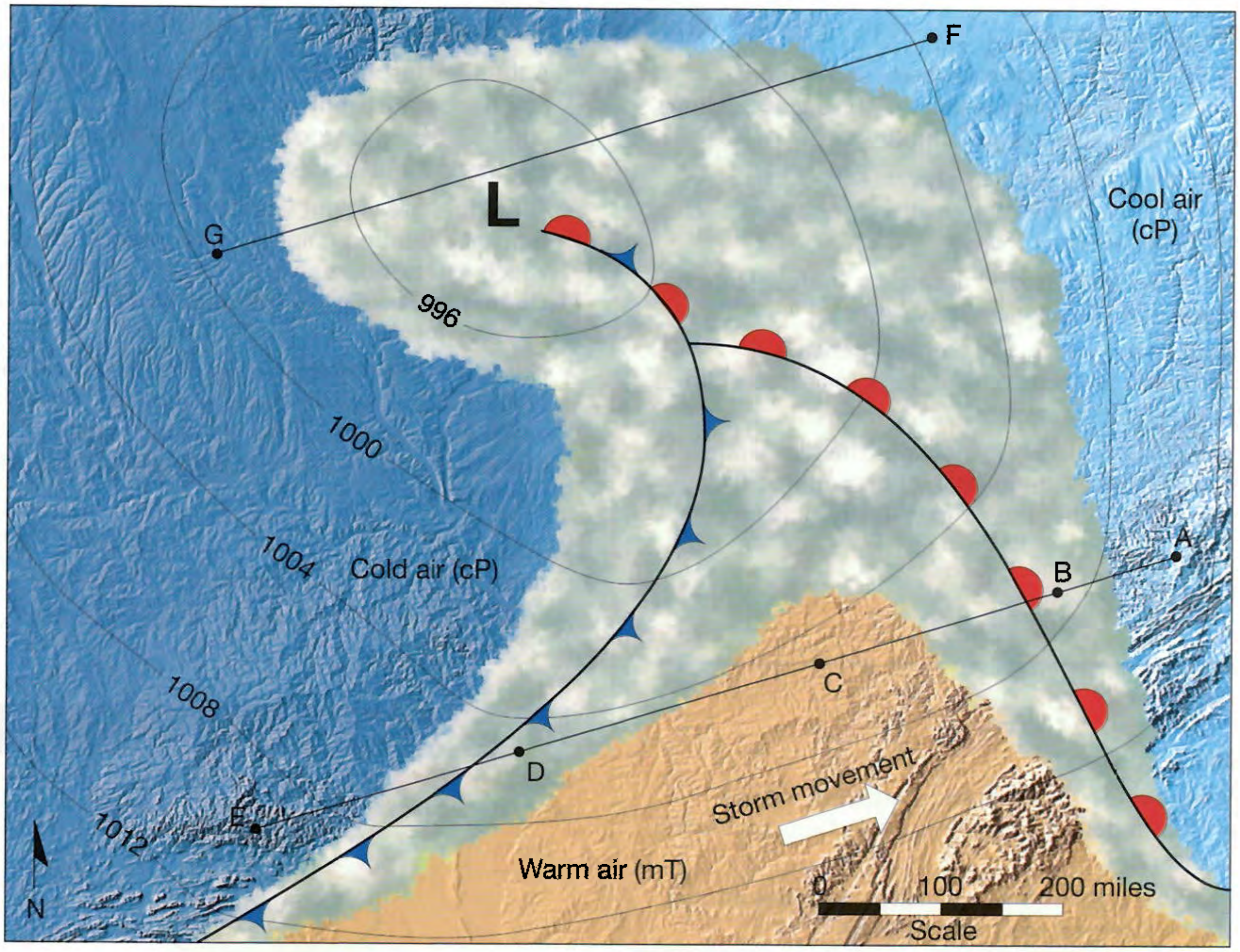
Skills Observing, Comparing and Contrasting, Predicting

Procedure

1. Use the paper clips or removable tape to secure the tracing paper over the map on the facing page.
2. Carefully trace all of the features and boundaries on the map. Be sure to include the isobars—the lines that show atmospheric pressure. Use the ruler to trace lines EA and GF.
3. Remove the tracing paper. Place it next to the map.
4. Transfer all of the letters and numbers on the map to your tracing.
5. Use the colored pencils to color the land and water areas on the tracing. Also color the symbols used to designate the fronts.
6. Identify and label the cold front, warm front, and occluded front on your tracing.
7. Draw arrows that show the direction of surface winds at points A, C, E, F, and G.

Analyze and Conclude

1. **Describing** In which direction are the surface winds moving?
2. **Identifying** At which stage of formation is the cyclone? Explain your answer. Refer to Figure 14 if necessary.
3. **Explaining** Is the air in the center of the cyclone rising or falling? What effect does this have on the potential for condensation and precipitation?
4. **Inferring** Find the center of the low, which is marked with the letter L. What type of front has formed here? What happens to the maritime tropical air in this type of front?



5. **Predicting** Once the warm front passes, in which direction will the wind at point B blow?
6. **Synthesizing** Describe the changes in wind direction and moisture in the air that will likely occur at point D after the cold front passes.
7. **Synthesizing** Describe the wind directions, humidity, and precipitation expected for a city as the cyclone moves and the city's relative position changes from point A to B, point C, point D, and finally from point D to E.

Go Further Find out and explain how subpolar lows affect middle-latitude cyclones over the United States in winter.

CHAPTER 20 Study Guide

20.1 Air Masses

Key Concepts

- An air mass is an immense body of air that is characterized by similar temperatures and amounts of moisture at any given altitude.
- As an air mass moves, its characteristics can change and so does the weather in the area over which the air mass moves.
- Air masses are classified according to their source region, the place where they form.
- Much of the weather in North America is influenced by continental polar (cP) and maritime tropical (mT) air masses.
- Polar (P) or tropical (T) indicates the temperature of an air mass. Continental (c) or maritime (m) indicates whether the air mass is dry or humid.

Vocabulary
air mass, *p. 559*

20.2 Fronts

Key Concepts

- When two air masses meet, they form a front, which is a boundary that separates two contrasting air masses.
- A warm front forms when warm air moves into an area formerly covered by cooler air.
- A cold front forms when cold, dense air moves into a region occupied by warmer air.
- A stationary front forms when the surface position between two air masses does not move.
- An occluded front forms when a cold front overtakes a warm front, producing a complex weather pattern.
- A middle-latitude cyclone is a large center of low pressure that generally travels from west to east and causes stormy weather.

Vocabulary
front, *p. 564;* warm front, *p. 565;* cold front, *p. 566;* stationary front, *p. 566;* occluded front, *p. 567*

20.3 Severe Storms

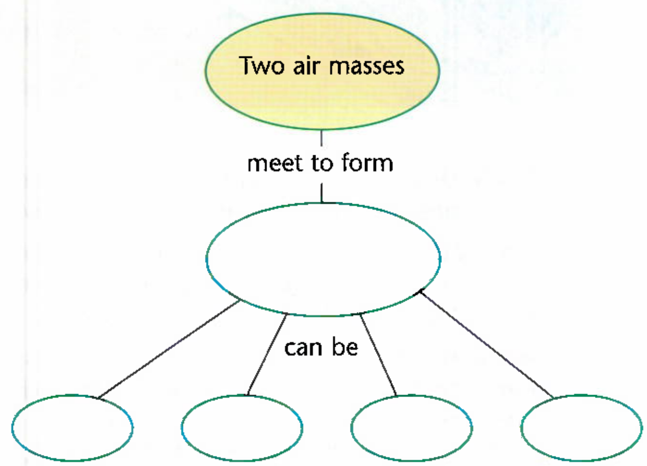
Key Concepts

- A thunderstorm generates thunder and lightning and frequently produces gusty winds, heavy rain, and hail. Thunderstorms form when warm, humid air rises in an unstable environment.
- Tornadoes are violent windstorms that take the form of a rotating column of air called a vortex, which extends downward from a cumulonimbus cloud. Most tornadoes are associated with severe thunderstorms.
- Hurricanes are whirling tropical cyclones with high winds that sometimes develop over the ocean when water temperatures are warm enough to provide the necessary heat and moisture to fuel the storms.

Vocabulary
thunderstorm, *p. 571;* tornado, *p. 573;* hurricane, *p. 575;* eye wall, *p. 576;* eye, *p. 576;* storm surge, *p. 577*

Thinking Visually

Concept Map Use what you know about fronts and air masses to complete this concept map.



CHAPTER 20

Assessment

Interactive textbook with assessment at PHSchool.com

Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. If an area is experiencing consecutive days of constant weather, this weather is called
   - **a.** air-mass weather.
   - **b.** warm-front weather.
   - **c.** cold-front weather.
   - **d.** occluded-front weather.

2. An air mass that forms over the Gulf of Mexico is a(n)
   - **a.** cP air mass.
   - **b.** mP air mass.
   - **c.** cT air mass.
   - **d.** mT air mass.

3. Air masses that have the greatest influence on weather in the midwestern United States are
   - **a.** mT and cT air masses.
   - **b.** cP and mT air masses.
   - **c.** mP and cP air masses.
   - **d.** cT and cP air masses.

4. Lake-effect snow is associated with a(n)
   - **a.** mP air mass.
   - **b.** mT air mass.
   - **c.** cP air mass.
   - **d.** cT air mass.

5. "Rain long foretold, long last; short notice, soon past." The first five words of this weather proverb refer to a(n)
   - **a.** warm front.
   - **b.** cold front.
   - **c.** anticyclone.
   - **d.** tornado.

6. Which front often produces hours of moderate-to-light precipitation over a large area?
   - **a.** polar
   - **b.** maritime
   - **c.** cold
   - **d.** warm

7. A thunderstorm is most intense during its
   - **a.** cumulus stage.
   - **b.** wave stage.
   - **c.** mature stage.
   - **d.** dissipating stage.

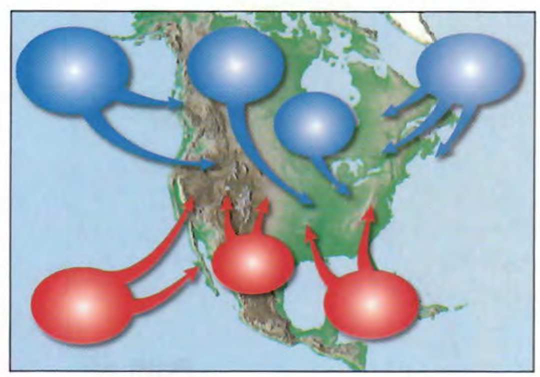
8. When a hurricane reaches land, its intensity decreases as the result of
   - **a.** increase in pressure and temperature.
   - **b.** lack of cold, dry air to fuel the storm.
   - **c.** successive updrafts into the eye wall.
   - **d.** friction and the lack of warm, moist air.

9. The eye of a hurricane
   - **a.** has the greatest wind speeds.
   - **b.** is warmer than the rest of the storm.
   - **c.** experiences high pressures.
   - **d.** is responsible for heavy precipitation.

Understanding Concepts

10. What kinds of changes occur as an air mass moves over an area?
11. Describe the effects of cP and mT air masses on much of the weather in the United States.
12. Describe weather associated with a warm front.
13. What kind of weather is associated with a cold front while it is over an area and once it passes?
14. What is a stationary front?
15. Sequence the steps that lead to the formation of an occluded front.
16. Describe the stages involved in the development of a middle-latitude cyclone.
17. How are cyclones and anticyclones related?
18. Describe the formation of a thunderstorm.
19. What is a mesocyclone and how does it form?
20. Describe the different parts of a hurricane.

Use this map to answer Questions 21–24.



21. Name the three red air masses and identify the source region of each.
22. Identify the cold air masses, starting with the air mass farthest west and moving eastward.
23. Which air masses would supply the largest amount of precipitation to the area east of the Rocky Mountains?
24. Which of the air masses has the greatest influence on weather along the northwest coast?

Critical Thinking

25. Comparing and Contrasting Compare and contrast polar air masses with tropical air masses.

26. Synthesizing What type of air mass is responsible for most of the warm fronts east of the Rocky Mountains?

27. Inferring What kinds of weather conditions would you expect in regions north of a middle-latitude cyclone during winter?

28. Comparing and Contrasting Compare and contrast tornadoes and hurricanes.

29. Identifying Cause and Effect Great damage and significant loss of life can take place a day or more after a hurricane has moved ashore and weakened. Explain why this might happen.

Map Skills

Use the map to answer Questions 30–34.

30. Reading Maps Over which ocean did Hurricane Floyd develop and move?

31. Interpreting Graphs On which days was Floyd a tropical storm?

32. Describing Describe the path of Hurricane Floyd from September 10 through September 16.

33. Inferring When was Hurricane Floyd most intense? Explain.

34. Reading Maps When and where did Hurricane Floyd move onto land?

Concepts in Action

35. Synthesizing Describe weather conditions that you would observe if the center of a middle-latitude cyclone passed north of you.

36. Applying Concepts What kinds of negative effects might a hurricane have on coastal ecosystems?

37. Writing in Science Use what you know about weather patterns to write a paragraph to explain which parts of the Earth system interact to produce the high snowfall in the Great Lakes region of North America.

Performance-Based Assessment

Applying Concepts Find out about precautions people should take during any of the three types of severe storms discussed in this chapter. Summarize your findings in three separate posters.

Standardized Test Prep

Test-Taking Tip

Using Maps
Most maps in Earth science are used to show geographic features such as mountains and bodies of water, tectonic features such as plate boundaries, and different types of rocks. Maps, like those shown below, can also be used to show statistical information. When using such maps to answer questions, be sure you understand what each map is showing before you try to answer the questions.

Use the maps below and what you know about thunderstorms and tornadoes to answer the questions on this page.

Choose the letter that best answers the question or completes the statement.

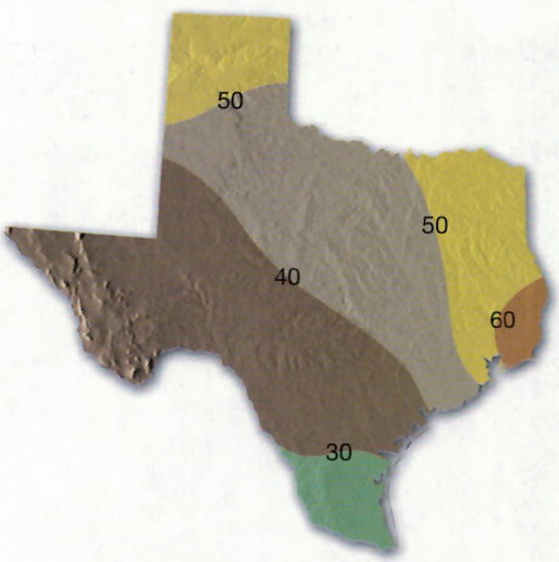
1. What part of Texas experiences the greatest average number of days with thunderstorms per year?
   (A) the southernmost tip
   (B) the southwestern portion of the state
   (C) the northern panhandle
   (D) the southeastern corner

2. The part of Texas that experiences the greatest average number of tornadoes per 26,000 km^2 is the area colored
   (A) tan.
   (B) green.
   (C) yellow.
   (D) orange.

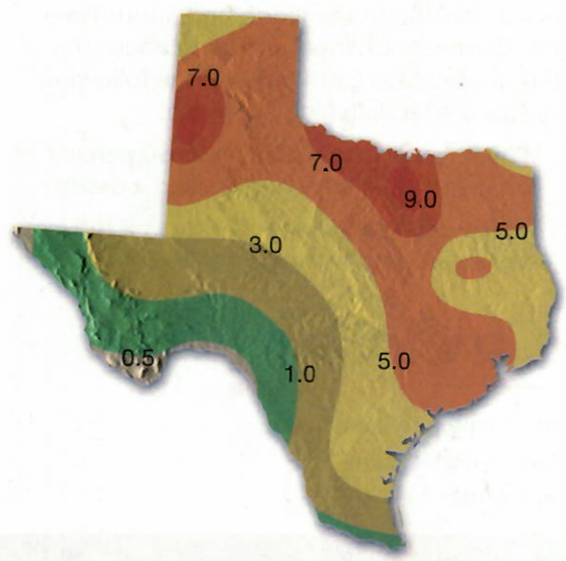
3. How many tornadoes on average are experienced in the area referred to in Question 2?
   (A) 1.0–2.0
   (B) 2.0–3.0
   (C) 5.0–7.0
   (D) 7.0–9.0

Answer the following question in complete sentences.

4. Does there appear to be a relationship between the number of days with thunderstorms and the average number of tornadoes in Texas? Explain.



Average Number of Days/Year with Thunderstorms



Average Annual Tornadoes per 26,000 km^2

CHAPTER

21 Climate

CONCEPTS in Action

Quick Lab
Observing How Land and Water Absorb and Release Energy

Exploration Lab
Human Impact on Climate and Weather

How the Earth Works
Coniferous Forests

GEODe EARTH SCIENCE
Heating the Atmosphere
↳ The Greenhouse Effect

Discovery Channel School **Video Field Trip**
Polar Weather

Take a field trip to the North and South Poles with Discovery Channel and learn about the coldest places on Earth. Answer the following questions after watching the video.

1. Why is Antarctica, which holds 80 percent of the world's ice, technically called a desert?
2. What would happen to the ocean if the ice shelves around Antarctica melted?

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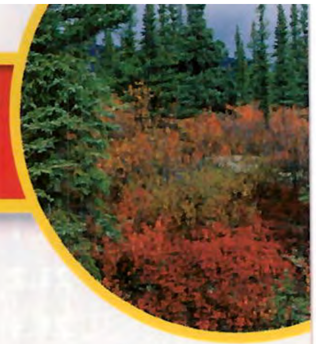
Climate determines the types of vegetation that grow in an area. This forest in Denali Park, Alaska, includes a mix of coniferous forest and tundra vegetation. ▶

21.1 Factors That Affect Climate



Reading Focus

Key Concepts

- How does latitude affect climate?
- How does elevation affect climate?
- What effect does a mountain range have on climate?
- How do large bodies of water affect climate?
- What effect do global winds have on climate?
- How does vegetation affect climate?

Vocabulary

- tropical zone
- temperate zone
- polar zone

Reading Strategy

Summarizing Information Copy the table. As you read, summarize the effect(s) each factor has on climate.

Factor	Effect(s) on Climate
1. Latitude	a. ____?____
2. Elevation	b. ____?____
3. Topography	c. ____?____
4. Water bodies	d. ____?____
5. Global wind	e. ____?____
6. Vegetation	f. ____?____

Figure 1 Maroon Bells Area, Colorado All of Earth's spheres interact to affect climate.
Identifying ***In the photograph, identify at least two components of each of the spheres shown.***

Recall from Chapter 17 that climate includes not only the average weather conditions of an area, but also any variations from those norms. In this section, you will learn that climate involves more than just the atmosphere. Powered by the sun, the climate system is a complex exchange of energy and moisture among Earth's different spheres, all of which are shown in Figure 1.

Factors That Affect Climate

The varied nature of Earth's surface and the many interactions that occur among Earth's spheres give every location a distinctive climate. You will now find out how latitude, elevation, topography, large bodies of water, global winds, and vegetation affect the two most important elements of climate—temperature and precipitation.

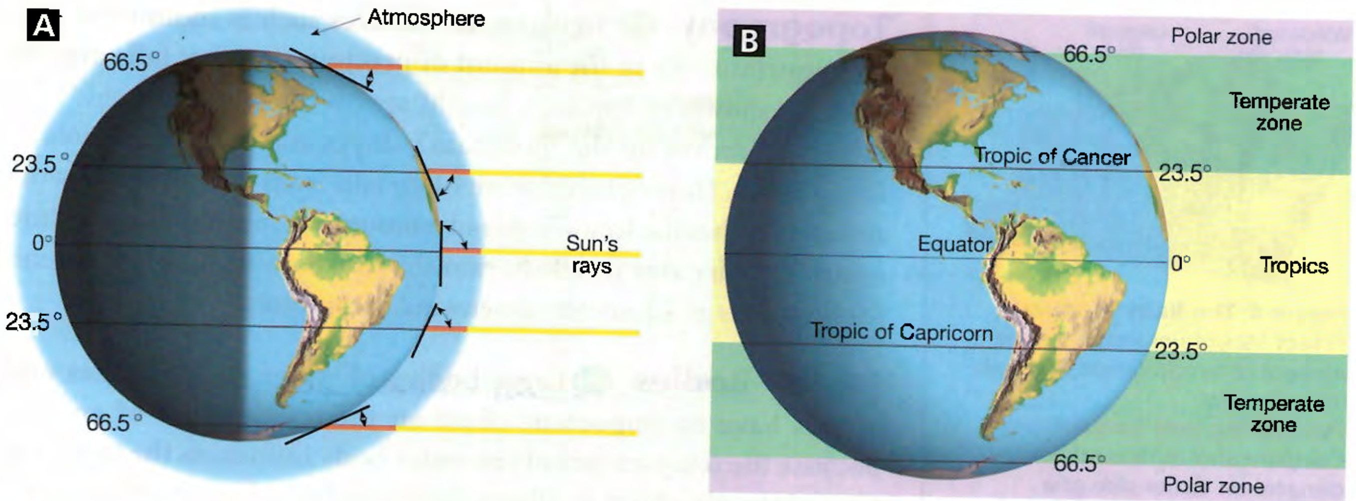


Figure 2 Earth's Major Climate Zones A Solar energy striking Earth's surface near the poles is less intense than radiation striking near the equator.
B Earth can be divided into three zones based on these differences in incoming solar radiation.

Latitude

Latitude is the distance north or south of the equator. **As latitude increases, the intensity of solar energy decreases.** Can you explain why? Study Figures 2A and 2B. Notice that near the equator, the sun's energy strikes the planet at nearly right angles. Therefore, in this region, between about 23.5° north (Tropic of Cancer) and 23.5° south (Tropic of Capricorn) of the equator, the sun's rays are most intense. This region is called the tropics, or the **tropical zones.** Temperatures in the tropical zones are generally warm year-round. In the **temperate zones,** which are between about 23.5° and 66.5° north and south of the equator, the sun's energy strikes Earth at a smaller angle than near the equator. This causes solar energy to be spread out over a larger area. In addition, the length of daylight in the summer is much greater than in the winter. As a result, temperate zones have hot summers and rather cold winters. In the **polar zones,** which are between 66.5° north and south latitudes and the poles, the energy strikes at an even smaller angle, causing the light and heat to spread out over an even larger area. Therefore, the polar regions experience very cold temperatures, even in the summer.

Elevation

Elevation, or height above sea level, is another factor that affects the climate of an area. Recall from Chapter 17 that air temperature decreases with elevation by an average of about 6.5°C Celsius every 1000 meters. **The higher the elevation is, the colder the climate.** The elevation of an area also determines the amount of precipitation it receives. Examine the graph in Figure 3 to see how the climates of two cities at roughly the same latitude are affected by their height above sea level.

Reading Checkpoint *How does the intensity of solar radiation vary at different parts of Earth?*

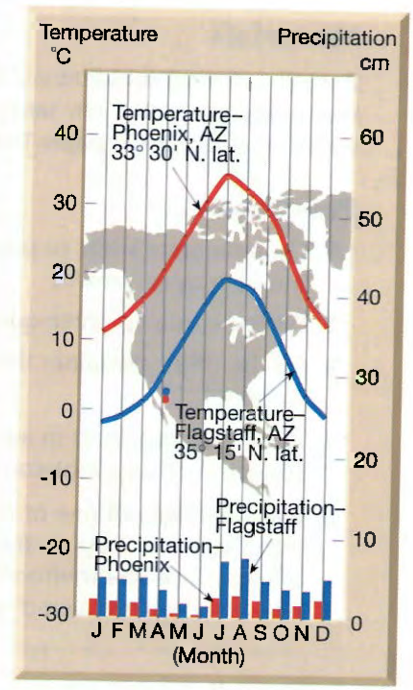


Figure 3 Climate Data for Two Cities This climate graph shows data for two cities in Arizona. Phoenix has an elevation of 338 m. Flagstaff has an elevation of 2134 m.
Interpreting Graphs ***How does elevation affect annual temperatures and precipitation?***

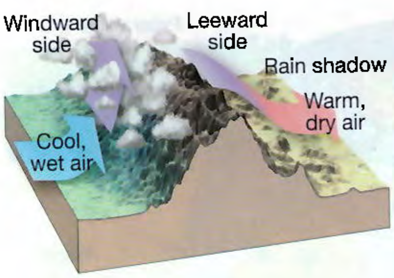


Figure 4 The Rain Shadow Effect Mountains influence the amount of precipitation that falls over an area.
Comparing and Contrasting ***Compare and contrast the climates on either side of a mountain.***

Topography **Topographic features such as mountains play an important role in the amount of precipitation that falls over an area.** As shown in Figure 4, humid air on the windward side of a mountain moves up the mountain's slopes and eventually cools to form clouds. Heavy precipitation often falls from these clouds. By the time air reaches the leeward side of a mountain, much of the moisture is lost. This dry area is called a rain shadow. Rain shadows can extend for hundreds of kilometers downwind of a mountain range.

Water Bodies **Large bodies of water such as lakes and oceans have an important effect on the temperature of an area because the temperature of the water body influences the temperature of the air above it.** Places downwind of a large body of water generally have cooler summers and milder winters than places at the same latitude that are farther inland. In the Quick Lab below, you can observe how a body of water can influence climate.

Quick Lab

Observing How Land and Water Absorb and Release Energy

Materials

2 small, identical containers; 2 laboratory thermometers; water; dry sand; masking tape; watch or clock; book; paper towels or rags for spills

Procedure

1. On a separate sheet of paper, make a copy of the data table shown.
2. Fill one container three-quarters full of dry sand.
3. Fill the other container three-quarters full of water.
4. Place the containers in a sunny area on a flat surface such as a tabletop or a lab bench.
5. Place the bulb of one of the thermometers into the sand. Prop up the thermometer with a book. Tape the thermometer in place so that only the bulb is covered with sand.
6. Repeat Step 5 with the water.
7. Record the initial temperature of each substance in your data table.
8. Record the temperature of each thermometer every 5 minutes for about 20 minutes.
9. Remove the containers from the sunny area.
10. Record the temperature of each thermometer for another 20 minutes.

Analyze and Conclude

1. **Comparing and Contrasting** Which substance heated faster? Which substance cooled faster?
2. **Drawing Conclusions** How does a large body of water affect the temperature of nearby areas?

Heat Absorption and Retention of Water and Sand

	Time	Temp H_2O	Temp Sand		Time	Temp H_2O	Temp Sand
Sunny Area	0			Shady Area	0		
	5				5		
	10				10		
	15				15		
	20				20		

Atmospheric Circulation

Global winds are another factor that influences climate because they distribute heat and moisture around Earth. Recall from Chapter 19 that winds constantly move warm air toward the poles and cool air toward the equator. The low-pressure zones at the equator and in the subpolar regions lead to the formation of clouds that drop precipitation as rain or snow.

Figure 5 Arizona Vegetation
A Cacti and scrub are common types of vegetation in the hot, dry climate of Phoenix, Arizona.
B The vegetation in the highlands of Flagstaff, Arizona, is much different.
Formulating Hypotheses ***Which of these areas would receive more precipitation? Why?***

Vegetation You probably already know that the types of plants that grow in a region depend on climate, as shown in Figures 5A and 5B. But did you know that vegetation affects climate? **Vegetation can affect both temperature and the precipitation patterns in an area.** Vegetation influences how much of the sun's energy is absorbed and how quickly this energy is released. This affects temperature. During a process called transpiration, plants release water vapor from their leaves into the air. So, transpiration influences precipitation. Studies also indicate that some vegetation releases particles that act as cloud seeds. This increase in particles promotes the formation of clouds, which also influences regional precipitation patterns.

Section 21.1 Assessment

Reviewing Concepts

1. How does latitude affect climate?
2. How does elevation affect climate?
3. How does a mountain range affect climate?
4. How do large bodies of water affect climate?
5. What effect do global winds have on climate?
6. Describe different ways in which vegetation affects climate.

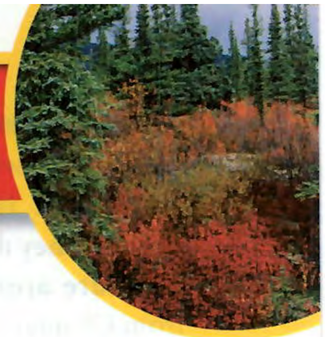
Critical Thinking

7. **Comparing and Contrasting** Compare and contrast tropical zones, temperate zones, and polar zones in terms of location and the intensity of solar radiation that each receives.
8. **Explaining** Explain why deserts are common on the leeward sides of mountain ranges.
9. **Applying Concepts** Look again at Figures 3 and 5. What two factors contribute to the average annual temperature in both areas?

Writing in Science

Explanatory Paragraph Write a paragraph to explain how three of the factors discussed in this section affect the climate of your area.

21.2 World Climates



Reading Focus

Key Concepts

- What is the Köppen climate classification system?
- What are humid tropical climates?
- Contrast the different types of humid mid-latitude climates.
- What are the characteristics of dry climates?
- What are the characteristics of polar climates?
- How do highland climates compare with nearby lowlands?

Vocabulary

- Köppen climate classification system
- wet tropical climate
- tropical wet and dry climate
- humid subtropical climate
- marine west coast climate
- dry-summer subtropical climate
- subarctic climate

Reading Strategy

Outlining Copy and continue the outline for each climate type discussed in this section. Include temperature and precipitation information for each climate type, as well as at least one location with that climate type.

I. **World Climates**
   A. Humid tropical
      1. Wet tropics
      2. ____?____
   B. Humid mid-latitude
      1. ____?____
      2. ____?____
   C. Dry
      1. ____?____
      2. ____?____

Figure 6 An ice cap climate is a polar climate in which the average monthly temperature is always below freezing.

If you were to travel around the world, you would find an incredible variety of climates. So many, in fact, that it might be hard to believe they could all occur on the same planet! Despite the diversity, climates can be classified according to average temperatures and amount of precipitation. In this section, you will learn about the Köppen climate classification system, which is commonly used to group climates.

The Köppen Climate Classification System

Many classification systems have been used to group climates. Perhaps the best-known and most commonly used system is the Köppen climate classification system. **The Köppen climate classification system uses mean monthly and annual values of temperature and precipitation to classify climates.** This system is often used because it classifies the world into climatic regions in a realistic way.

The Köppen system has five principal groups: humid tropical climates, dry climates, humid mid-latitude climates, polar climates, and highland climates. An example of a polar climate is shown in Figure 6. Note that all of these groups, except climates classified as dry, are defined on the basis of temperature. Dry climates are classified according to the amount of precipitation that falls over an area. Each of the five major groups is further subdivided. See Figure 9 on page 594.

Figure 7 Rain Forest in Malaysia The vegetation in the tropical rain forest is the most luxuriant found anywhere on Earth.

Humid Tropical Climates

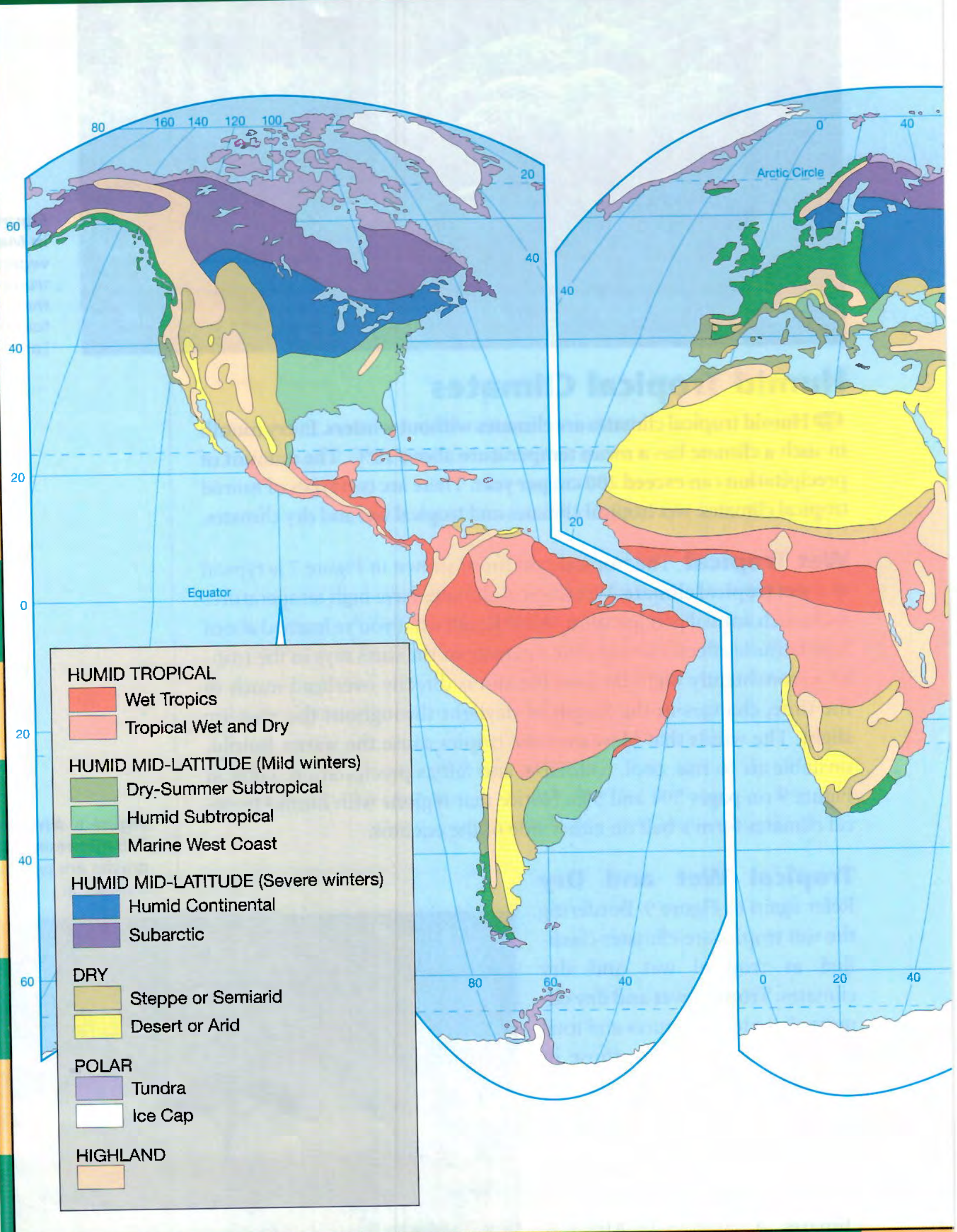
Humid tropical climates are climates without winters. Every month in such a climate has a mean temperature above 18°C. The amount of precipitation can exceed 200 cm per year. There are two types of humid tropical climates: wet tropical climates and tropical wet and dry climates.

Wet Tropical The tropical rain forest shown in Figure 7 is typical of a **wet tropical climate.** Wet tropical climates have high temperatures and much annual precipitation. Why? Recall what you've learned about how latitude affects climate. The intensity of the sun's rays in the tropics is consistently high. Because the sun is directly overhead much of the time, changes in the length of daylight throughout the year are slight. The winds that blow over the tropics cause the warm, humid, unstable air to rise, cool, condense, and fall as precipitation. Look at Figure 9 on pages 594 and 595. Notice that regions with humid tropical climates form a belt on either side of the equator.

Tropical Wet and Dry Refer again to Figure 9. Bordering the wet tropics are climates classified as tropical wet and dry climates. **Tropical wet and dry climates** have temperatures and total precipitation similar to those in the wet tropics, but experience distinct periods of low precipitation. Savannas, which are tropical grasslands with drought-resistant trees, are typical of tropical wet and dry climates. A savanna in Africa is shown in Figure 8.

Figure 8 African Savanna Drought-resistant trees and tall grasses are typical vegetation of a savanna.

Global Climates



MAP MASTER™ Skills Activity

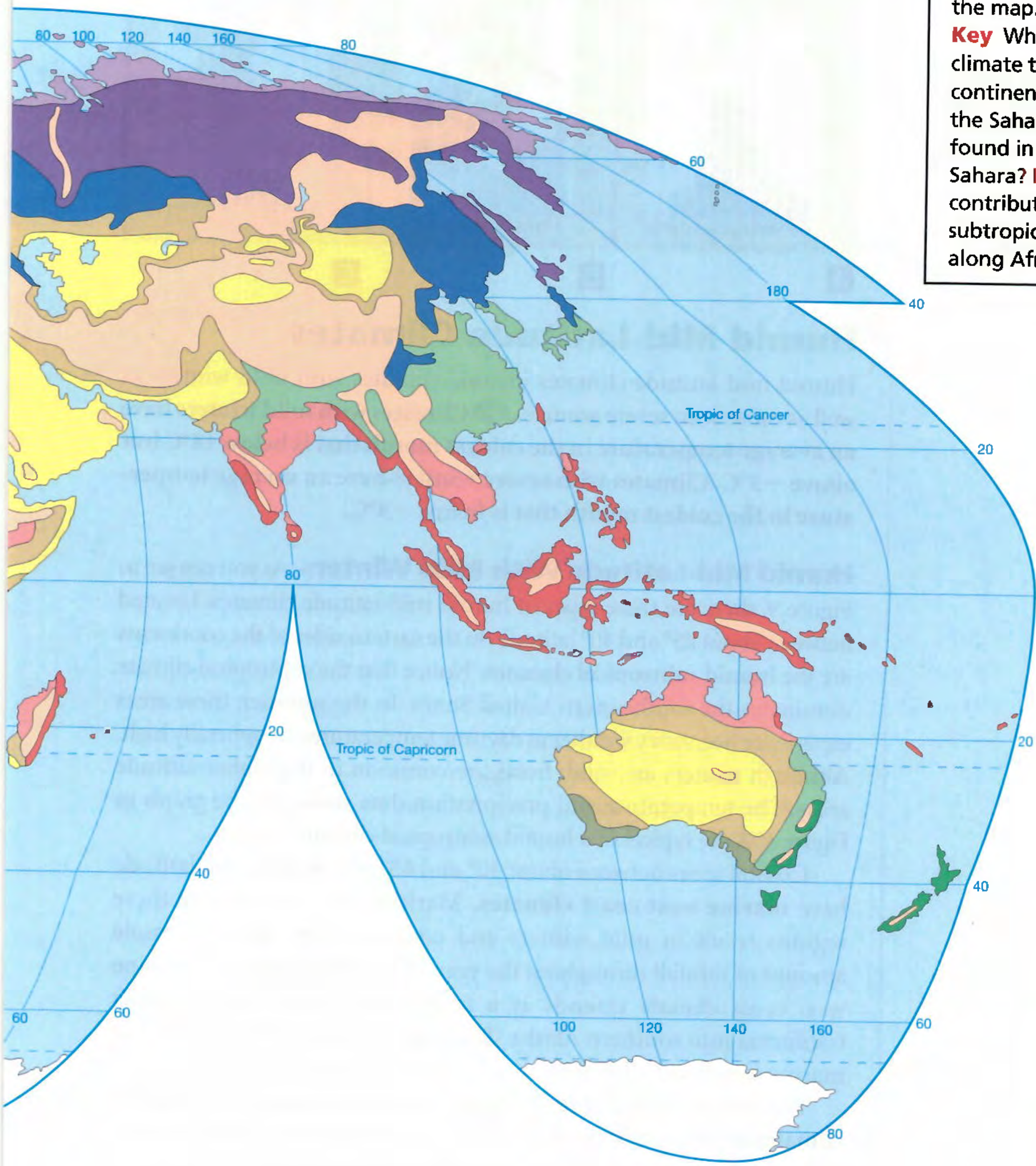


Figure 9

Regions Find Africa on the map. **Use the Map Key** What are the major climate types of this continent? **Locate** Locate the Sahara. What climate is found in the region of the Sahara? **Infer** What may contribute to the subtropical marine climate along Africa's southern tip?

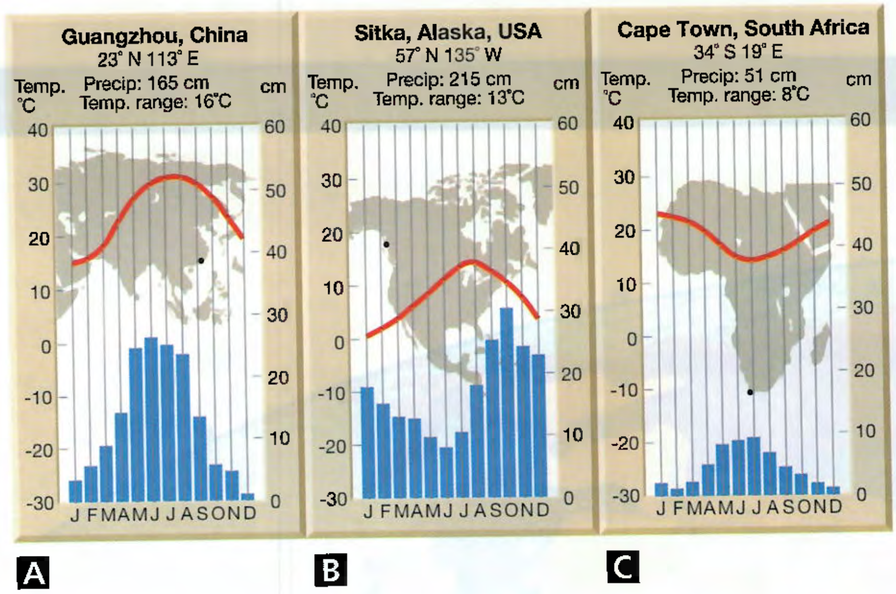


Figure 10 Each of these graphs shows typical climate data of the mid-latitude climates with mild winters. Graph **A** shows a humid subtropical climate. Graph **B** shows a marine west coast climate. Graph **C** shows a dry-summer subtropical climate.

Humid Mid-Latitude Climates

Humid mid-latitude climates include climates with mild winters as well as those with severe winters. **Climates with mild winters have an average temperature in the coldest month that is below 18°C but above −3°C. Climates with severe winters have an average temperature in the coldest month that is below −3°C.**

Humid Mid-Latitude With Mild Winters As you can see in Figure 9, there are three types of humid mid-latitude climates. Located between about 25° and 40° latitude on the eastern sides of the continents are the **humid subtropical climates.** Notice that the subtropical climate dominates the southeastern United States. In the summer, these areas experience hot, sultry weather as daytime temperatures are generally high. Although winters are mild, frosts are common in the higher-latitude areas. The temperature and precipitation data shown in the graph in Figure 10A are typical of a humid subtropical climate.

Coastal areas between about 40° and 65° north and south latitude have **marine west coast climates.** Maritime air masses over these regions result in mild winters and cool summers with an ample amount of rainfall throughout the year. In North America, the marine west coast climate extends as a narrow belt from northernmost California into southern Alaska. The data in Figure 10B are typical of marine west coast climates.

As you can see in Figure 9, regions with **dry-summer subtropical climates** are located between about 30° and 45° latitude. These climatic regions are unique because they are the only humid climate that has a strong winter rainfall maximum, as shown in Figure 10C. In the United States, dry-summer subtropical climate is found only in California. It is sometimes referred to as a mediterranean climate.

Reading Checkpoint *Describe the conditions typical of a humid subtropical climate.*

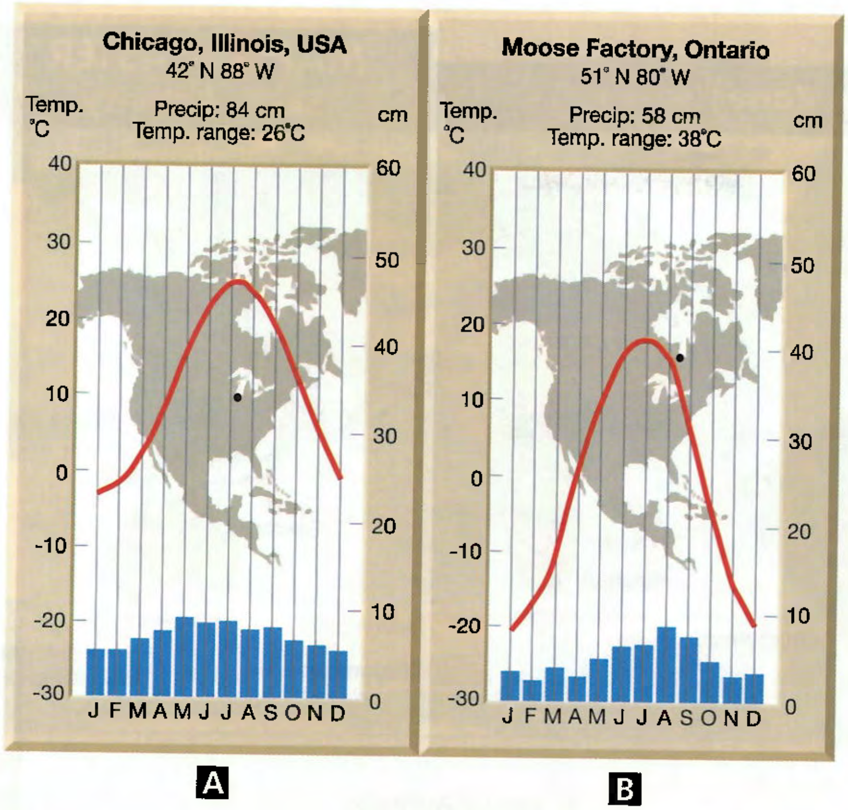


Figure 11 Graph **A** displays data typical of a humid continental climate. The trends shown in graph **B** are typical of a subarctic climate.
Interpreting Graphs ***What are the typical temperatures and amounts of precipitation for Chicago, Illinois, in May and June?***

Humid Mid-Latitude With Severe Winters There are two types of humid mid-latitude climates with severe winters: the humid continental climates and the subarctic climates. Continental landmasses strongly influence both of these climates. As a result, such climates are absent in the Southern Hemisphere. There, oceans dominate the middle-latitude zone. Locate the regions having a humid continental climate, which are shown in blue, on Figure 9. Note that areas with such climates lie between approximately 40° and 50° north latitude. As you can see in Figure 11A the winters are severe, while the summers are typically quite warm. Note, too, that precipitation is generally greater in summer than in winter.

North of the humid continental climate and south of the tundra is an extensive **subarctic climate** region. From Figure 9, you can see that this climate zone covers a broad expanse. Such climates stretch from western Alaska to Newfoundland in North America, and from Norway to the Pacific coast of Russia in Eurasia. Winters in these regions are long and bitterly cold. By contrast, summers in the subarctic are remarkably warm but very short. The extremely cold winters and relatively warm summers combine to produce the highest annual temperature ranges on Earth.

Reading Checkpoint ***Compare and contrast two types of humid mid-latitude climates with severe winters.***

Extent of Dry Climate Zones

MAP MASTER™ Skills Activity

Figure 12

Location Locate each of the places listed. **Identify** Identify the desert(s) in each place or region.

1. Chile
2. southwestern United States
3. central Australia
4. northwestern India
5. southern Africa

Describe About how much of Australia has a desert climate?

Q & A

Q *Are deserts always hot?*

A Deserts can certainly be hot places. The record high temperature for the United States, 57°C, was set at Death Valley, California. However, deserts also experience very cold temperatures. The average daily minimum in January in Phoenix, Arizona, is 1.7°C, a temperature just barely above freezing. At Ulan Bator in Mongolia's Gobi Desert, the average high temperature in January is only −19°C!

Dry Climates

A dry climate is one in which the yearly precipitation is not as great as the potential loss of water by evaporation. In other words, dryness is not only related to annual rainfall, but is also a function of evaporation. Evaporation, in turn, is closely dependent upon temperature. There are two types of dry climates: arid or desert and semi-arid or steppe, as shown in Figure 12. These two climate types are classified as BW and BS, respectively, in the Köppen classification system. Arid and semi-arid climates have many features in common. In fact, the difference between them is slight. The steppe is a marginal and more humid variant of the desert. The steppe represents a transition zone that surrounds the desert and separates it from humid climates.

Dry climates exist as the result of the global distribution of air pressure and winds. In regions near the tropics of Cancer and Capricorn, air is subsiding. When air sinks, it is compressed and warmed. Such conditions are opposite of those needed for clouds to form precipitation. As a result, regions with dry climates experience mostly clear, sunny skies and dry climates. Other dry areas including the Great Basin in North America and the Gobi Desert of Eurasia occur where prevailing winds meet mountain barriers. These arid regions are called rain shadow deserts.

Polar Climates

Polar climates are those in which the mean temperature of the warmest month is below 10°C. Winters in these regions are periods of perpetual night, or nearly so, making temperatures at most polar locations extremely cold. During the summer months, temperatures remain cool despite the long days. Very little precipitation falls in polar regions. Evaporation, too, in these areas is limited.

There are two types of polar climates. The tundra climate, like that shown in Figure 13, is a treeless region found almost exclusively in the Northern Hemisphere. The ice cap climate does not have a single monthly mean above 0°C. Little vegetation grows and the landscape in these regions is covered by permanent ice and snow. Ice cap climates occur in scattered high mountain areas and in Greenland and Antarctica.

Figure 13 Tundra North of Nome, Alaska Tundra plant life includes mostly mosses, shrubs, and flowering herbs.

Highland Climates

The climate types discussed so far are very similar from place to place and extend over large areas. Some climates, however, are localized, which means that they are much different from climates in surrounding areas. One such climate is a highland climate. Conditions of highland climates often vary from one place to another. For example, south-facing slopes are warmer than north-facing slopes, and air on the windward sides of mountains is wetter than air on the leeward sides. **In general, highland climates are cooler and wetter than nearby areas at lower elevations.** Locate the highland climate regions on Figure 9. What do they all have in common?

Go Online
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For: Links on climates of the world
Visit: www.SciLinks.org
Web Code: cjn-6212

Section 21.2 Assessment

Reviewing Concepts

1. What is the Köppen climate classification system?
2. Describe the characteristics of humid tropical climates.
3. What are some characteristics of humid mid-latitude climates?
4. What defines a dry climate?
5. What are the characteristics of polar climates?
6. How do highland climates compare with nearby lowlands?

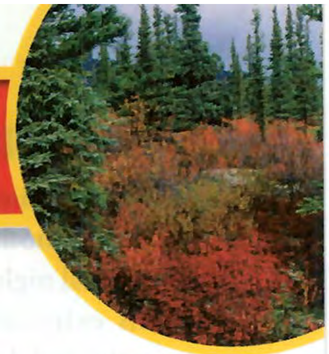
Critical Thinking

7. **Identifying** Use Figure 9 to identify the climate type of your city. Describe some characteristics of your city's climate type.
8. **Formulating Conclusions** Can tundra climates exist at low latitudes? Explain.

Writing in Science

Explanatory Paragraph Write a paragraph in which you explain why Antarctica can be classified as a desert.

21.3 Climate Changes



Reading Focus

Key Concepts

- Describe natural processes that can cause changes in climate.
- What is the greenhouse effect?
- What is global warming?
- What are some of the consequences of global warming?

Vocabulary

- greenhouse effect
- global warming

Reading Strategy

Identifying Cause and Effect Copy the table. Identify the causes and effects of climate change presented in this section.

Climate Changes	
Causes	Effects
a. ?	b. ?
c. ?	d. ?
e. ?	f. ?

Like most conditions on Earth, climate is always changing. Some of these changes are short-term. Others occur over long periods of geologic time. Some climate changes are the result of natural processes, such as the volcanic eruption shown in Figure 14. Others are related to human activities. In this section, you will learn about some of the ways in which climate changes.

Natural Processes That Change Climate

Many different natural processes can cause a climate to change. Some of the climate-changing processes that you will learn about include volcanic eruptions as well as changes in ocean circulation, solar activity, and Earth motions.

Figure 14 Eruption of Mount Pinatubo

Volcanic Eruptions As you can see in Figure 14, volcanic eruptions can emit large volumes of ash and dust into Earth's atmosphere. What you can't see in the photograph is that volcanic eruptions also send minute particles containing sulfur, into the air. If the volume of these very fine particles called aerosols, is great enough, it can cause short-term changes in Earth's surface temperature. Can you hypothesize why? **The presence of aerosols (volcanic ash, dust, and sulfur-based aerosols) in the air increases the amount of solar radiation that is reflected back into space. This causes Earth's lower atmosphere to cool.**

Ocean Circulation Recall from Chapter 19 that El Niño is a change in ocean circulation that causes parts of the eastern tropical Pacific Ocean to become warmer than usual. **These changes in ocean circulation also can result in short-term climate fluctuations.** For example, some areas that are normally arid receive large amounts of rain during El Niño. Refer to Figure 15. Also, some regions that receive abundant precipitation may experience dry periods when ocean circulation patterns change.

Figure 15 Effect of El Niño In 1998, bad weather conditions and flooding in Alabama were attributed to El Niño.

Solar Activity The most studied hypotheses for the causes of climate change are based on changes in the output of solar energy. When the sun is most active, it contains dark blemishes called sunspots. The formation of sunspots appears to correspond with warm periods in Europe and North America. Although variations in solar output may cause short-term climatic change, no evidence for long-term variations due to solar activity exist.

Earth Motions A number of Earth motions are thought to cause changes in climate. Most of these changes are long-term changes. Tectonic plate movements, for example, cause the crust and upper mantle to move slowly over Earth's surface. These movements cause ocean basins to open and close. Plate movements also cause changes in the positions of landmasses. **These geographic changes in Earth's land and water bodies cause changes in climate.**

Changes in the shape of Earth's orbit and the tilt of Earth on its axis are other Earth motions that affect global climates. Earth's orbit, or path around the sun, is always elliptical. But over a 100,000-year period, the path becomes more and then less elliptical. This change in shape brings Earth closer to and then farther from the sun. This affects global climates. Like its orbit, the tilt of Earth on its axis changes about 2 degrees over a 41,000-year period. Because the angle of tilt varies, the severity of the seasons also changes. The smaller the tilt, the smaller the temperature difference between summer and winter.

Reading Checkpoint *Identify four natural processes that can result in climate changes.*

Human Impact on Climate Changes

Natural processes have certainly contributed to many climatic changes throughout Earth's 4.6-billion year history. These processes will also be responsible for some of the future shifts in Earth's climates. Besides these processes of nature, human activities have contributed and will contribute to global climatic change.

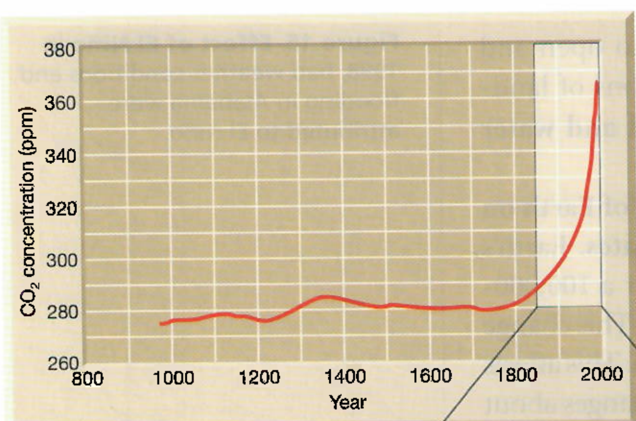
The Greenhouse Effect

The greenhouse effect is a natural warming of both Earth's lower atmosphere and Earth's surface. The major gases involved in the greenhouse effect are water vapor and carbon dioxide. These greenhouse gases, as they are often called, are transparent to incoming solar radiation and therefore much of this energy reaches Earth's surface. Most of this energy is then reradiated skyward. The greenhouse gases are good absorbers of Earth's radiation, which accounts for the warm temperatures of the lower atmosphere.

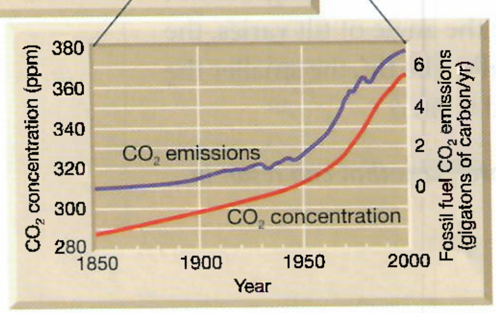
The greenhouse effect is very important because it makes life as we know it possible on Earth. Without this effect, Earth would be much too cold to support any kind of complex life forms. However, an increase in the greenhouse effect could also prove devastating to Earth's billions of organisms.

Studies indicate that human activities for the past 200 or so years have had a huge impact on the greenhouse effect. As you can see in Figure 16, carbon dioxide levels in the air have risen at a rapid pace since about 1850. Much of this greenhouse gas has been added by the burning of fossil fuels such as coal, petroleum, and natural gas. The clearing of forests also contributes to an increase in carbon dioxide because this gas is released when vegetation is burned or when it decays.

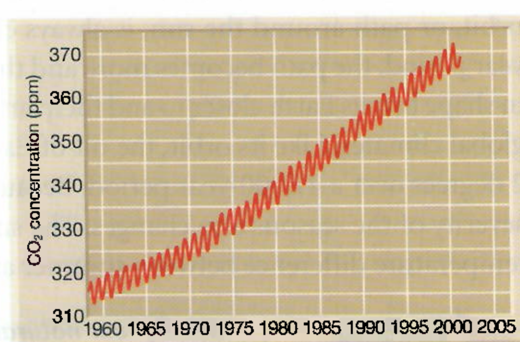
Figure 16 The rapid increase in carbon dioxide concentration since 1850 has closely followed the increase in carbon dioxide emissions from burning fossil fuels. **Inferring** ***What do you think initiated this increase in carbon dioxide levels?***



A



B



C

Global Warming **As a result of increases in carbon dioxide levels, as well as other greenhouse gases, global temperatures have increased. This increase is called global warming.** Refer to Figure 17. Note that during the twentieth century, Earth's average surface temperatures increased about 0.6°C. Scientists predict that by the year 2100, temperatures will increase by 1.4°C to 5.8°C. How will these temperature increases affect Earth?

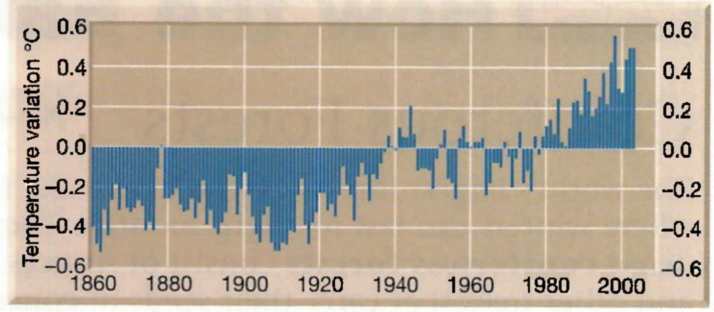


Figure 17 Increases in the levels of greenhouse gases have caused changes in Earth's average surface temperatures.
Interpreting Graphs ***What year was the warmest to date?***

Warmer surface temperatures increase evaporation rates. This, in turn, increases the amount of water vapor in the atmosphere. Water vapor is an even more powerful absorber of radiation emitted by Earth than is carbon dioxide. Therefore, more water vapor in the air will magnify the effect of carbon dioxide and other gases.

Temperature increases will also cause sea ice to melt. Ice reflects more incoming solar radiation than liquid water does. The melting of the ice will cause a substantial increase in the solar energy absorbed at the surface. This, in turn, will magnify the temperature increase created by higher levels of greenhouse gases. The melting of sea ice and ice sheets will also cause a global rise in sea level. This will lead to shoreline erosion and coastal flooding.

Scientists also expect that weather patterns will change as a result of the projected global warming. More intense heat waves and droughts in some regions and fewer such events in other places are also predicted. What other consequences of global warming do you think might occur?

Go Online SCiLINKS NSTA

For: Links on the carbon cycle/global warming
Visit: www.SciLinks.org
Web Code: cjn-6213

Section 21.3 Assessment

Reviewing Concepts

1. Describe four natural processes that can cause climate change.
2. What is the greenhouse effect?
3. What is global warming?
4. What are some of the possible effects of global warming?

Critical Thinking

5. **Formulating Hypotheses** Which would have a longer effect on climate changes—volcanic ash and dust or the same volume of sulfur-based aerosols? Why?
6. **Formulating Conclusions** How do you think cloud cover might change as the result of global warming?
7. **Synthesizing** How might global warming affect Earth's inhabitants, including humans?

Writing in Science

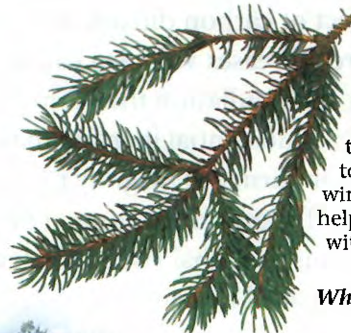
Persuasive Paragraphs Write at least two paragraphs to persuade your friends and family to reduce their consumption of fossil fuels. Be sure to explain why the usage of such energy sources should be reduced.

Coniferous Forests

The world's largest forests extend across the far north, where winters can last for eight months. These dense **coniferous forests** consist of spruces, pines, and other trees that carry their seeds in cones. They are particularly suited for coping with cold conditions. Animals in northern forests find plentiful food during the long days of summer, but the season is brief and cold weather soon returns. To survive the harsh winter, many animals migrate south, while others hibernate.

Distribution of northern coniferous forests

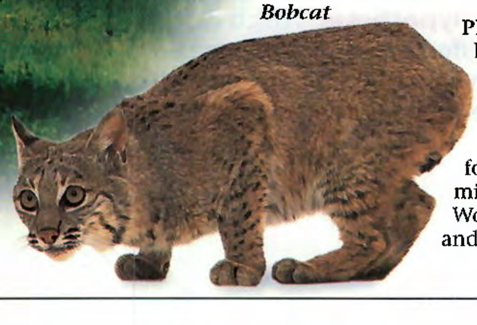
FORESTS AND LAKES
Coniferous forests often grow on land once covered by ice age glaciers. These glaciers scoured the ground, scraping away soil and creating rounded hills and hollows. When the glaciers melted, the hills became covered with trees and the hollows turned into lakes.



CONIFER LEAVES
Most conifers have small evergreen leaves that are tough enough to withstand the coldest winters. A narrow shape helps the leaves to cope with strong winds.

White spruce

Waterlogged soil beneath trees is acidic and infertile.



Bobcat

PREDATORS
Mammals are relatively scarce in northern forests, so the **predators** that feed upon other animals sometimes have to cover vast distances to find food. Bobcats may roam many miles searching for small prey. Wolves hunt in packs for deer and other large mammals.

1. A horntail lays eggs deep in a tree trunk.

2. Young larvae bore away from the drill-hole.

3. Each larva matures inside a chamber near the bark of the tree.

EATING WOOD
Several insects of northern forests feed on wood. The horntail, or giant wood wasp, lays eggs by drilling deep beneath tree bark with a long egg-laying tube. The larvae hatch and mature inside the tree while feeding on the wood.

Red crossbill

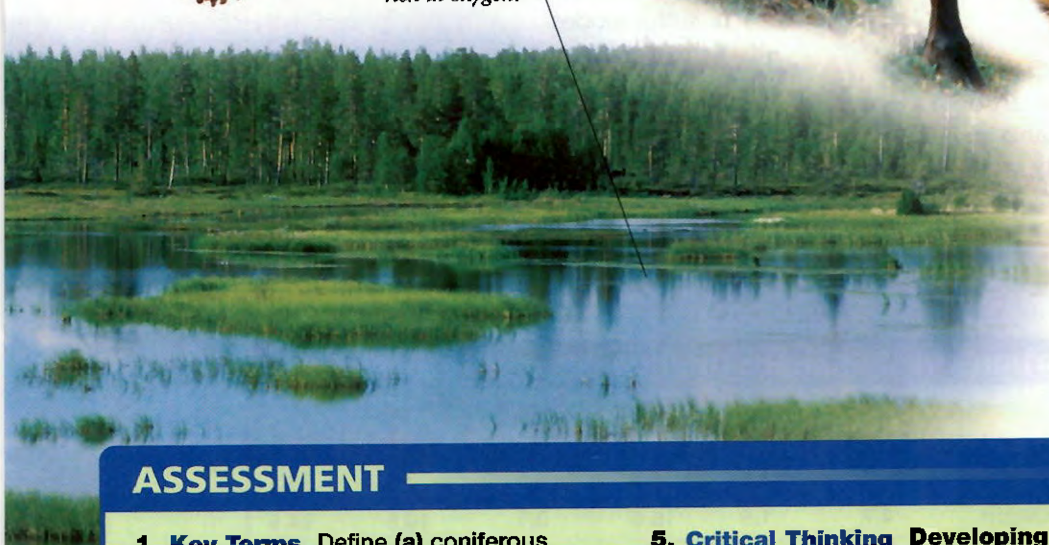
SEED EATERS
Some birds rely on conifer seeds for food. Crossbill finches have unique bills that are crossed at the tips. This helps them remove seeds from cones. Clark's nutcracker, a member of the crow family, hides 20,000 or more seeds each fall. It is able to remember the locations of many of these seeds for up to nine months.

Spruce cone

Caribou

Caribou hooves act as snowshoes.

ADAPTED FOR TRAVEL
To help them walk across thick layers of snow without sinking, caribou and elk have hooves with broadly splayed toes that help to distribute their weight. Lynx and snowshoe hares have similar adaptations.



Cold lake water contains few nutrients but is often rich in oxygen.

COPING WITH COLD
To avoid extreme winter temperatures, bears, woodchucks, and other mammals hibernate. During the fall, they build up a store of fat in their bodies that will last until spring. They then go into **hibernation,** which slows their bodily functions to a minimum.

Woodchuck

ASSESSMENT

1. **Key Terms** Define **(a)** coniferous forest, **(b)** predator, **(c)** hibernation.
2. **Climates** Describe the climatic conditions that are generally found in northern coniferous forests.
3. **Ecosystems** How do trees serve as a food source for birds and insects?
4. **Ecosystems** How are mammals of northern coniferous forests well suited for survival in their natural environment?
5. **Critical Thinking** **Developing a Hypothesis** Deforestation has not reduced northern coniferous forests to the same degree that it has reduced mid-latitude deciduous forests. Why do you think that northern coniferous forests have fared better than deciduous forests to the south?

Exploration Lab

Human Impact on Climate and Weather

Scientists are now closely monitoring how daily human activity is changing microclimates. There is concern that changing microclimates can have an effect on global climates. In this investigation, you will explore some of the ways that human activities are changing the atmosphere.

Problem How do we know that human activity is changing Earth's climates?

Materials

- paper
- pen or pencil

Skills Calculating, Measuring, Using Tables, Analyzing Data

Procedure

1. Table 1 lists many of the types, sources, and amounts of primary pollutants. Use this table to answer items 1, 2, 3, and 4 under Analyze and Conclude.
2. Look at Figure A. The pollutants listed are linked to a wide variety of negative health effects such as eye irritation, heart damage, and lung damage. The pollutants shown are also linked to reduced visibility, reduced crop yields, and damage to ecosystems. Study the figure and answer items 5, 6, and 7.
3. Look at Figure B. Scientists have noted the increasing levels of carbon dioxide in the atmosphere. Research continues to determine whether these increasing levels are affecting global climates. Use Figure B to answer item 8.
4. Look at Table 2. This table presents data on the effects of large cities on their surrounding microclimates. Temperatures in cities can be higher than the surrounding countryside. Meteorologists call this effect "the urban heat island". Study the data in the table and answer items 9, 10, and 11.

Analyze and Conclude

1. **Interpreting Data** What is the leading source (by weight) of primary pollutants? How many metric tons of this pollutant are added to the atmosphere each year?
2. **Interpreting Data** Which of the following is the most abundant primary pollutant?
   a. carbon monoxide
   b. sulfur oxides
3. **Calculating** Your answer for item 2 is what percentage of all primary pollutants?
   a. 25% b. 50% c. 75%
4. **Calculating** What is the approximate total weight (in million metric tons) of all primary pollutants added to the atmosphere?

Table 1 Estimated Nationwide Emissions (millions of metric tons/year)

Source	Carbon Monoxide	Partic-ulates	Sulfur Oxides	Volatile Organics	Nitrogen Oxides	Total
Transportation	43.5	1.6	1.0	5.1	7.3	58.5
Stationary Source Fuel Combustion	4.7	1.9	16.6	0.7	10.6	34.5
Industrial Processes	4.7	2.6	3.2	7.9	0.6	19.0
Solid Waste Disposal	2.1	0.3	0.0	0.7	0.1	3.2
Miscellaneous	7.2	1.2	0.0	2.8	0.2	11.4
Total	62.2	7.6	20.8	17.2	18.8	126.6

Source: U.S. Environmental Protection Agency

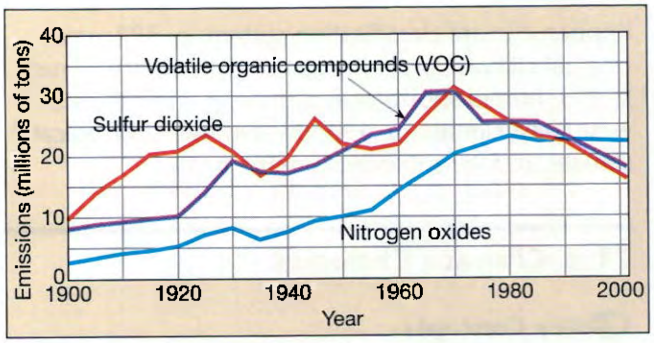


Figure A

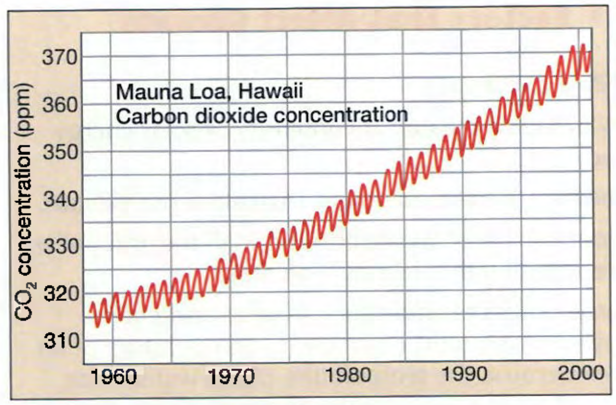


Figure B

5. **Interpreting Data** Describe the trend you see in the data for atmospheric pollutants prior to 1970.
6. **Interpreting Data** Describe the trend you see in the data for atmospheric pollutants since 1970.
7. **Inferring** Suggest a reason for the changing trend.
8. **Calculating** What has been the approximate percentage increase in atmospheric carbon dioxide near Mauna Loa since 1958?
9. **Interpreting Data** Compared to rural areas, which factors are increased by urbanization? Which factors are decreased?
10. **Interpreting Data** Of all of the factors shown, which shows the greatest increase due to urbanization?
11. **Predicting** Suggest a possible reason for each of the following effects on the weather that is influenced by a city.
    a. increased frequency of thunderstorms
    b. lower wind speed
    c. increased precipitation

Go Further Use the internet to search for climate data for your region. What trends do you see in the data since 1970? Suggest a hypothesis that could be used to test your conclusions.

Table 2 Average Climatic Changes Produced by Cities

Element	Comparison with Rural Areas
Particulate matter	10 times more
Temperature	
Annual mean	0.5–1.5°C higher
Winter	1–2°C higher
Solar radiation	15–30% less
Ultraviolet, winter	30% less
Ultraviolet, summer	5% less
Precipitation	5–15% more
Thunderstorm frequency	16% more
Winter	5% more
Summer	29% more
Relative humidity	6% lower
Winter	2% lower
Summer	8% lower
Cloudiness (frequency)	5–10% more
Fog (frequency)	60% more
Winter	100% more
Summer	30% more
Wind speed	25% lower
Calms	5–20% more

Source: After Landsberg, Changnon, and others.

CHAPTER 21

Study Guide

21.1 Factors That Affect Climate

Key Concepts

- As latitude increases, the intensity of solar energy decreases.
- The higher the elevation is, the colder the climate.
- Mountains play an important role in the amount of precipitation that falls over an area.
- Large bodies of water such as lakes and oceans have an important effect on the temperature of an area because the temperature of the water body influences the temperature of the air above it.
- Global winds affect climate because they distribute heat and moisture around Earth.
- Vegetation can affect both temperature and the precipitation patterns in an area.

Vocabulary

tropical zone, *p. 589;* temperate zone, *p. 589;* polar zone, *p. 589*

21.2 World Climates

Key Concepts

- The Köppen climate classification system uses mean values of temperature and precipitation to classify climates.
- Humid tropical climates have no winters.
- Humid mid-latitude climates with mild winters have an average temperature in the coldest month that is below 18°C but above −3°C. Humid mid-latitude climates with severe winters have an average temperature in the coldest month that is below −3°C.
- A dry climate is one in which the yearly precipitation is not as great as the potential loss of water by evaporation.
- Polar climates have a mean temperature in the warmest month that is below 10°C.
- Highland climates are generally cooler and wetter than nearby areas at lower elevations.

Vocabulary

Köppen climate classification system, *p. 592;* wet tropical climate, *p. 593;* tropical wet and dry climate, *p. 593;* humid subtropical climate, *p. 596;* marine west coast climate, *p. 596;* dry-summer subtropical climate, *p. 596;* subarctic climate, *p. 597*

21.3 Climate Changes

Key Concepts

- Aerosols, volcanic ash, dust, and sulfur-based aerosols in the air can cause a short-term cooling of the lower atmosphere.
- Changes in ocean circulation can result in short-term climate fluctuations.
- Changes in the shape of Earth's orbit and the tilt of Earth's axis affect global climates.
- The greenhouse effect is a natural warming of Earth's lower atmosphere and Earth's surface.
- As a result of increases in carbon dioxide levels, as well as other greenhouse gases, global temperatures have increased to cause global warming.
- Global warming causes changes in sea level.

Vocabulary

greenhouse effect, *p. 602;* global warming, *p. 603*

Thinking Visually

Identifying Causes and Effects Copy the table below onto a sheet of paper. Use the information in the chapter to complete the table.

Some Factors That Influence Climate	
Causes	**Effects**
1. Increase in latitude	1. ___?___
2. ___?___	2. Highland climate
3. Increase in greenhouse gases	3. ___?___
4. ___?___	4. More coastal erosion
5. Large volcanic eruption	5. ___?___
6. Nearby lake	6. ___?___

CHAPTER 21

Assessment

Interactive textbook with assessment at PHSchool.com

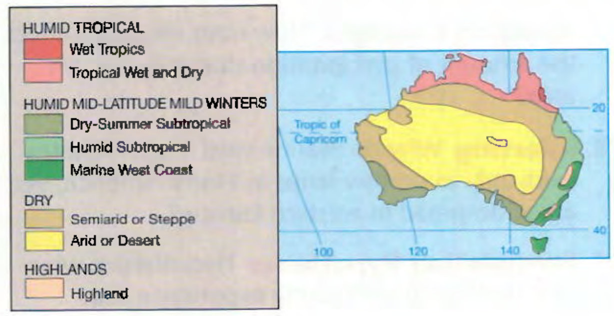
Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. Which of the following is true?
   - **a.** Climates at high latitudes are very warm.
   - **b.** A nearby lake causes a climate to be colder.
   - **c.** Vegetation can increase the amount of precipitation that falls over an area.
   - **d.** Places at lower elevations generally have lower temperatures.
2. Humid tropical climates always experience
   - **a.** severe winters.
   - **b.** dry summers.
   - **c.** low humidity.
   - **d.** warm temperatures.
3. In a dry climate, yearly precipitation is
   - **a.** less than the rate of evaporation.
   - **b.** greater than the rate of evaporation.
   - **c.** greater in a desert than a steppe.
   - **d.** less than that in a polar climate.
4. The greenhouse effect is best described as
   - **a.** an increase in Earth's surface temperature.
   - **b.** a natural warming effect of the atmosphere.
   - **c.** a result of global warming.
   - **d.** any short-term change in climate.
5. Recent global warming appears to be the result of
   - **a.** changes in global wind patterns.
   - **b.** a decrease in the greenhouse effect.
   - **c.** increases in greenhouse gases in the air.
   - **d.** changes in Earth's revolution around the sun.
6. Melting ice caps can result in which of the following?
   - **a.** a rise in sea level
   - **b.** a fall in sea level
   - **c.** colder temperatures
   - **d.** less precipitation
7. An increase in ocean temperatures can cause
   - **a.** melting of sea ice.
   - **b.** most forms of ocean life to flourish.
   - **c.** a decrease in sea level.
   - **d.** global wind patterns to stabilize.

Understanding Concepts

Use this map to answer Questions 8–10.



8. Describe the dominant climate in Australia.
9. Identify the type of climate found on the other parts of the continent.
10. What causes much of the east-southeastern part of the country to experience warm, humid, and marine west coast climates?
11. What powers Earth's climate system, and which of Earth's spheres are involved in this system?
12. Name the three major climate zones, and explain why their overall temperatures differ.
13. Why can two places at the same latitude have different climates?
14. What climate data are needed in order to classify a climate using the Köppen climate classification system?
15. Describe the characteristics of a wet tropical climate.
16. Describe the characteristics of a humid continental climate, and give one example of a place with such a climate.
17. Explain the greenhouse effect caused by Earth's atmosphere.
18. How have humans contributed to the increase in the levels of carbon dioxide in the atmosphere?
19. What is global warming?
20. How might global warming affect globa' precipitation?

Assessment *continued*

Critical Thinking

21. **Synthesizing** Can a region at low latitudes have snow? Explain.

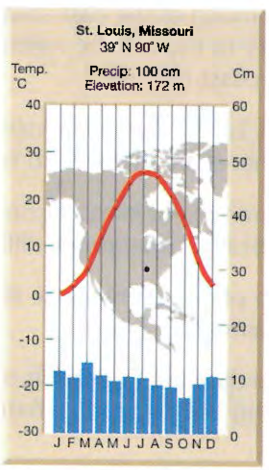
22. **Applying Concepts** How does elevation affect the amount of precipitation that falls over an area?

23. **Inferring** Why do marine west coast climates exist only as narrow strips in North America, yet are widespread in western Europe?

24. **Formulating Hypotheses** Hypothesize why rain shadow deserts rarely experience fog.

Using Graphs

Use the graph below to answer Questions 25–29.



25. **Reading Graphs** What is the highest average annual temperature, and during which month does it occur?

26. **Reading Graphs** What is the lowest annual temperature, and during which month does it occur?

27. **Calculating** What is the average annual temperature range for St. Louis?

28. **Inferring** What is the wettest season of the year in St. Louis?

29. **Classifying** Classify the climate of St. Louis using the Köppen climate classification system.

Concepts in Action

30. **Synthesizing** Cities are referred to as urban heat islands. Use what you know about factors that affect climate to explain this statement.

31. **Applying Concepts** What do you think can be done to reduce the steady increase in global carbon dioxide levels?

32. **Writing in Science** Suppose you're a writer for the school newspaper. You are doing a story on how global warming might affect your area. Write an article that explains at least three effects that an increase in Earth's surface temperature might have on the climate of your area.

Performance-Based Assessment

Applying Concepts Make flyers with catchy slogans to suggest ways to reduce your community's use of fossil fuels. Get permission to post the flyers in grocery stores, community halls, shopping malls, and other common areas.

Standardized Test Prep

Test-Taking Tip

Using More Than One Visual
Sometimes an answer to a test question requires that you use or interpret more than one visual. When this occurs, carefully study the visuals before you read the questions pertaining to them. Look for similarities and differences between the visuals. Refer to the visuals again as you read each of the questions associated with the visuals. Use the graphs to answer the questions on this page.

Choose the letter that best answers the question or completes the statement.

1. Earth's temperatures were similar to the temperatures on our planet today
   (A) about 150,000 years ago.
   (B) about 135,000 years ago.
   (C) about 50,000 years ago.
   (D) about 25,000 years ago.

2. When do you think Earth was covered with more ice than is on our planet today?
   (A) between 150,000 and 140,000 years ago
   (B) between 140,000 and 120,000 years ago
   (C) between 135,000 and 20,000 years ago
   (D) between 20,000 and 10,000 years ago

3. Which part of the temperature graph shows the global warming trend discussed in the chapter?
   (A) the time from about 170,000 to 140,000 years ago
   (B) the time from about 120,000 to 100,000 years ago
   (C) the time from about 70,000 to 60,000 years ago
   (D) the time from about 100 years ago to the present

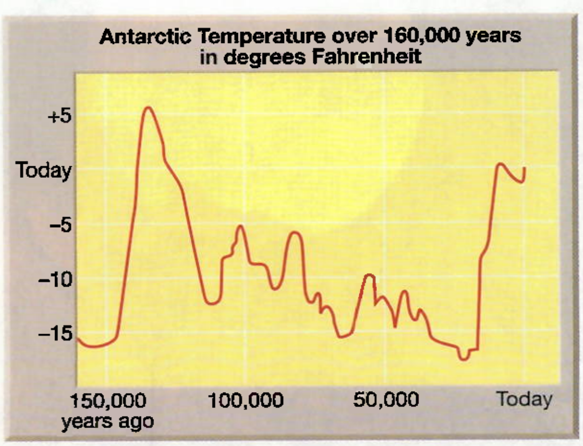
4. When during the past 160,000 years were carbon dioxide concentrations the highest?
   (A) about 150,000 years ago
   (B) about 120,000 years ago
   (C) about 40,000 years ago
   (D) about 1000 years ago

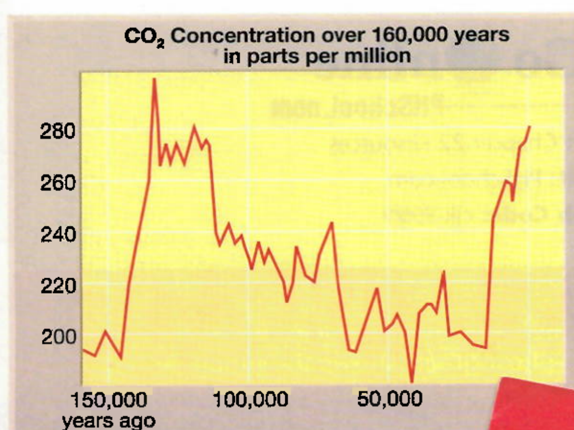
5. What were the carbon dioxide levels in the atmosphere during Earth's coldest period in the past 160,000 years?
   (A) between about 190 and 200 ppm
   (B) between about 220 and 240 ppm
   (C) between about 240 and 260 ppm
   (D) between about 260 and 280 ppm

Write one or two complete sentences to answer each of the following questions.

6. Describe the trends shown on the graphs.

7. Based on what you know about global warming and the data shown in these graphs, do you think the current global warming trends are natural changes or are they only the result of human activities? Support your answer with reasons.





CHAPTER 22

Origin of Modern Astronomy

CONCEPTS in Action

Exploration Lab
Modeling Synodic and Sidereal Months

Understanding Earth
Foucault's Experiment

GEODe EARTH SCIENCE
Astronomy
↳ Earth's Moon

DISCOVERY CHANNEL SCHOOL

Video Field Trip

Introduction to Space Exploration

Take a historical field trip with the Discovery Channel and find out about the history of space exploration. Answer the following questions after watching the video.

1. What was Galileo's major astronomical invention, and what theory did it enable him to confirm?
2. How was Pluto discovered?

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This photograph shows the moon ▶ over Mount Humphreys, in California's eastern Sierras.