16 The Atmosphere: Composition, Structure, and Temperature

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

16.1 Distinguish between weather and climate and name the basic elements of weather and climate.

16.2 List the major gases composing Earth's atmosphere and identify the components that are most important to understanding weather and climate.

16.3 Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows atmospheric layers based on temperature.

16.4 Explain what causes the Sun angle and length of daylight to change during the year and describe how these changes produce the seasons.

16.5 Distinguish between heat and temperature. List and describe the three mechanisms of heat transfer.

16.6 Sketch and label a diagram that shows the paths taken by incoming solar radiation. Summarize the greenhouse effect.

16.7 Calculate five commonly used types of temperature data and interpret a map that depicts temperature data using isotherms.

16.8 Discuss the principal controls of temperature and use examples to describe their effects.

16.9 Interpret the patterns depicted on world maps of January and July temperatures.

This power plant in Andalucia, Spain, produces clean thermoelectric power from the Sun. Solar radiation provides practically all the energy that heats Earth's surface and atmosphere. (Photo by Kevin Foy/Alamy)

Earth's atmosphere is unique. No other planet in our solar system has an atmosphere with the exact mixture of gases or the heat and moisture conditions necessary 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 we begin our examination of the ocean of air in which we all must live. We try to answer a number of basic questions: What is the composition of the atmosphere? Where does the atmosphere end, and where does outer space begin? What causes the seasons? How is air heated? What factors control temperature variations around the globe?

16.1 FOCUS ON THE ATMOSPHERE

Distinguish between weather and climate and name the basic elements of weather and climate.

Weather influences our everyday activities, our jobs, and our health and comfort. Many of us pay little attention to the weather unless we are inconvenienced by it or when it adds to our enjoyment outdoors. Nevertheless, there are few other aspects of our physical environment that affect our lives more than the phenomena we collectively call the weather.

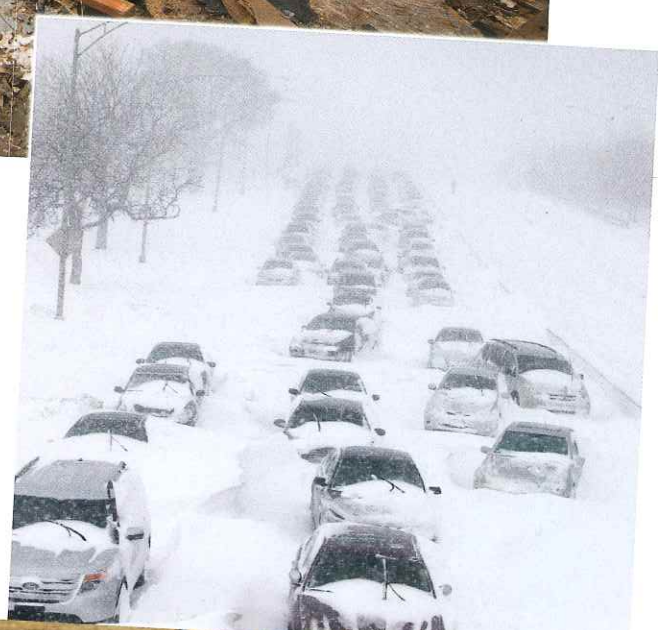


FIGURE 16.1 Memorable Weather Events Few aspects of our physical environment influence our daily lives more than the weather. The image on the right shows hundreds of cars stranded on Chicago's Lake Shore Drive during a blizzard on February 2, 2011. (Kiichiro Sato/AP Photo) The top photo shows the aftermath of the tornado that devastated Moore, Oklahoma, on May 20, 2013. (Photo by Julie Dermansky/Corbis)

Weather in the United States

The United States occupies an area that stretches from the tropics of Hawaii to beyond the Arctic Circle in Alaska. It has thousands of miles of coastline and extensive regions that are far from the influence of the ocean. Some landscapes are mountainous, and others are dominated by plains. It is a place where Pacific storms strike the West coast, and the East is sometimes influenced by events in the Atlantic and the Gulf of Mexico. Those in the center of the country commonly experience weather events triggered when frigid southward-bound Canadian air masses clash with northward-moving ones from the Gulf of Mexico.

Stories about weather are a routine part of the daily news. Articles and items about the effects of heat, cold, floods, drought, fog, snow, ice, and strong winds are commonplace. Of course, storms of all kinds are frequently front-page news (**FIGURE 16.1**). Beyond its direct impact on the lives of individuals, the weather has a strong effect on the world economy, influencing agriculture, energy use, water resources, transportation, and industry.

Weather clearly influences our lives a great deal. Yet, it is important to realize that people influence the atmosphere and its behavior as well (**FIGURE 16.2**). There are, and will continue to be, significant political and scientific decisions that must be made involving these impacts. Important examples are air pollution control and the effects of human activities on global climate and the atmosphere's protective ozone layer. So there is a need for increased awareness and understanding of our atmosphere and its behavior.

Weather and Climate

Acted on by the combined effects of Earth's motions and energy from the Sun, our planet's formless and invisible envelope of air reacts by producing an infinite variety of weather, which in turn creates the basic pattern of global climates. Although not identical, weather and climate have much in common.

Weather is constantly changing, sometimes from hour to hour and at other times from day to day. It is a term that refers to the state of the atmosphere at a given time and place. Whereas changes in the weather are continuous and sometimes seemingly erratic, it is nevertheless possible to arrive at a generalization of these variations. Such a description of aggregate weather conditions is termed **climate**. It is based on observations that have been accumulated over many years. Climate is often defined simply as "average weather," but this is an inadequate definition. To more accurately portray the character of an area, variations and extremes must also be included, as well as the probabilities that such departures will take place. For example, farmers need to know the average rainfall during the growing season, and they also need to know the frequency of extremely wet and extremely dry years. Thus, climate is the sum of all statistical weather information that helps describe a place or region.

Suppose you were planning a vacation trip to an unfamiliar place. You would probably want to know what kind of weather to expect. Such information would help as you selected clothes to pack and could influence decisions regarding activities you might engage in during your stay. Unfortunately, weather forecasts that go beyond a few days are not very dependable. Therefore, you might ask someone who is familiar with the area about what kind of weather to expect. "Are thunderstorms common?" "Does it get cold at night?" "Are the afternoons sunny?" What you are seeking is information about the climate, the conditions that are typical for that place. Another useful source of such information is the great variety of climate tables, maps, and graphs that are available. For example, the graph in **FIGURE 16.3** shows average daily high and low temperatures for each month, as well as extremes for New York City.

Such information could no doubt help as you planned your trip. But it is important to realize that *climate data cannot predict the weather*. Although a place may usually

FIGURE 16.2 People Influence the Atmosphere Smoke bellows from a coal-fired electricity-generating plant in New Delhi, India, in June 2008. (Gurinder Osan/AP Photo)

EYE ON EARTH

This is a scene on a summer day in a portion of southern Utah called Sinbad Country. Hebes Mountain is in the center of the image. (Photo by Michael Collier)

QUESTION 1 *Write two brief statements about this place—one that clearly relates to weather and another that might be part of a description of climate.*

QUESTION 2 *Explain the reasoning associated with each statement.*

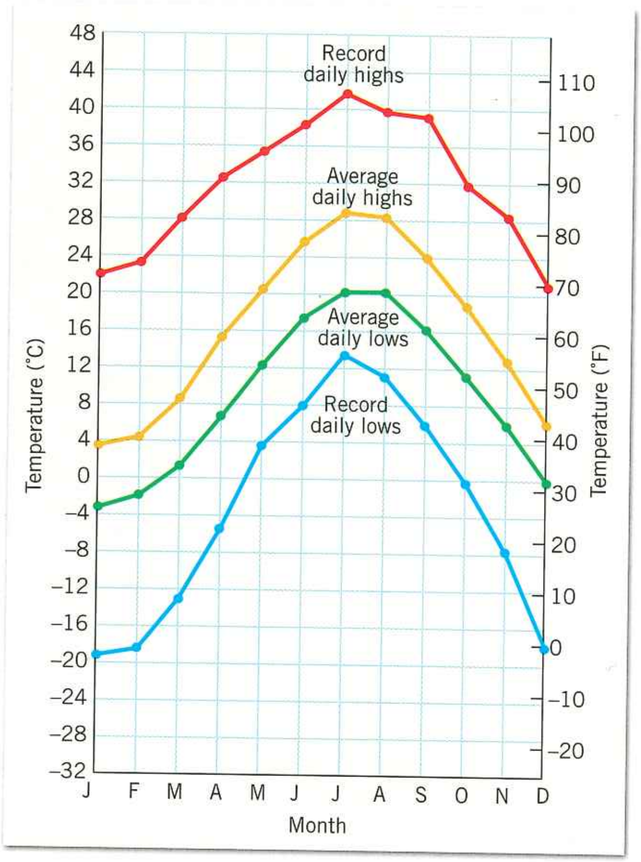


FIGURE 16.3 Graphs Can Display Climate Data This graph shows daily emperature data for New York City. In addition to the average daily maximum and minimum temperatures for each month, extremes are also shown. As this graph shows, there can be significant departures from he average.

(climatically) be warm, sunny, and dry during the time of your planned vacation, you may actually experience cool, overcast, and rainy weather. There is a well-known saying that summarizes this idea: "Climate is what you expect, but weather is what you get."

The nature of weather and climate is expressed in terms of the same basic **elements**—quantities or properties that are measured regularly. The most important elements are (1) air temperature, (2) humidity, (3) type and amount of cloudiness, (4) type and amount of precipitation, (5) air pressure, and (6) the speed and direction of the wind. These elements are the major variables from which weather patterns and climate types are deciphered. Although you will study these elements separately at first, keep in mind that they are very much interrelated. A change in any one of the elements will often bring about changes in the others.

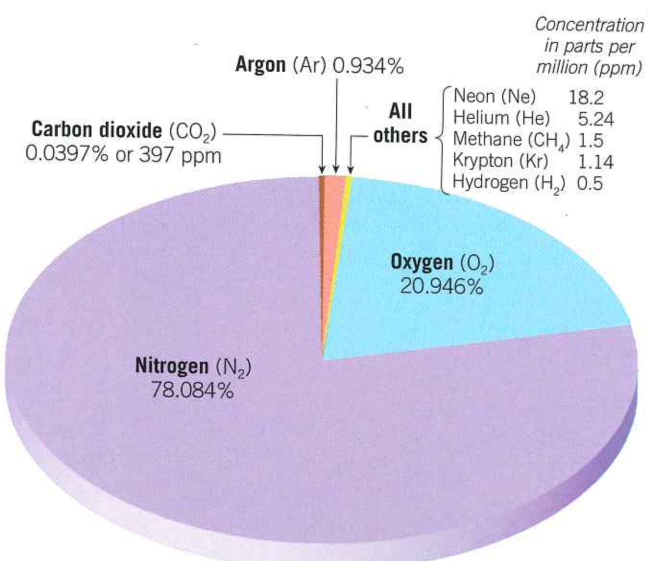
16.1 CONCEPT CHECKS

1. Distinguish between weather and climate.
2. Write two brief statements about your current location: one that relates to weather and one that relates to climate.
3. What is an *element*?
4. List the basic elements of weather and climate

16.2 COMPOSITION OF THE ATMOSPHERE

List the major gases composing Earth's atmosphere and identify the components that are most important to understanding weather and climate.

Sometimes the term *air* is used as if it were a specific gas, but it is not. Rather, **air** is a *mixture* of many discrete gases, each with its own physical properties, in which varying quantities of tiny solid and liquid particles are suspended.



IGURE 16.4 omposition of the tmosphere This graph ows the proportional lume of gases composing y air. Nitrogen and oxygen early dominate.

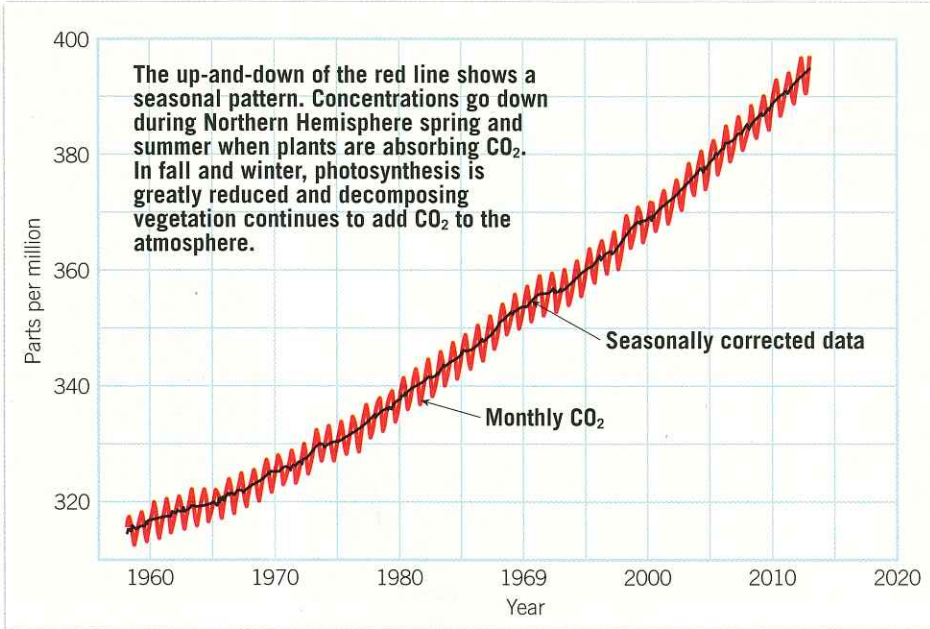
Major Components

The composition of air is not constant; it varies from time to time and from place to place. If the water vapor, dust, and other variable components were removed from the atmosphere, we would find that its makeup is very stable worldwide up to an altitude of about 80 kilometers (50 miles).

As you can see in **FIGURE 16.4**, two gases—nitrogen and oxygen—make up 99 percent of the volume of clean, dry air. Although these gases are the most plentiful components of air and are of great significance to life on Earth, they are of minor importance in affecting weather phenomena. 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 (CO_2)

Carbon dioxide, although present in only minute amounts (0.0397 percent, or 397 parts per million [ppm]), is nevertheless an important constituent of air. Carbon dioxide is of great interest to meteorologists because it is an efficient absorber of energy emitted by Earth and thus influences the heating of the atmosphere. Although the proportion of carbon dioxide in the atmosphere is relatively uniform, its percentage has been rising steadily for 200 years. **FIGURE 16.5** is a graph that shows the growth in atmospheric CO_2 since 1958. Much of this rise is attributed to the burning of ever-increasing quantities of fossil fuels, such as coal and oil. Some of this additional carbon dioxide is absorbed by the ocean or is used by plants, but more than 40 percent remains in the air. Estimates project that by sometime in the second half of the twenty-first century, CO_2 levels will be twice as high as the pre-industrial level.



SmartFigure 16.5
Monthly CO_2 Concentrations
Atmospheric CO_2 has been measured at Mauna Loa Observatory, Hawaii, since 1958. There has been a consistent increase since monitoring began. This graphic portrayal is known as the *Keeling Curve*, in honor of the scientist who originated the measurements. (NOAA)

Most atmospheric scientists agree that increased carbon dioxide concentrations have contributed to a warming of Earth's atmosphere over the past several decades and will continue to do so in the decades to come. The magnitude of such temperature changes is uncertain and depends partly on the quantities of CO_2 contributed by human activities in the years ahead. The role of carbon dioxide in the atmosphere and its possible effects on climate are examined in Chapter 20.

Variable Components

Air includes many gases and particles whose quantities vary significantly from time to time and place to place. Important examples include water vapor, dust particles, and ozone. Although usually present in small percentages, they can have significant effects on weather and climate.

Water Vapor You are probably familiar with the term *humidity* from watching weather reports on TV. Humidity is a reference to water vapor in the air. As you will learn in Chapter 17, there are several ways to express humidity. The amount of water vapor in the air varies considerably, from practically none at all up to about 4 percent by volume. Why is such a small fraction of the atmosphere so significant? The fact that water vapor is the source of all clouds and precipitation would be enough to explain its importance. However, water vapor has other roles. Like carbon dioxide, water vapor absorbs heat given off by Earth as well as some solar energy. It is therefore important when we examine the heating of the atmosphere.

When water changes from one state to another (see Figure 17.2, page 519), it absorbs or releases heat. This energy is termed *latent heat*, which means "hidden heat." As we shall see in later chapters, water vapor in the atmosphere transports this latent heat from one region to another, and it is the energy source that helps drive many storms.

Aerosols The movements of the atmosphere are sufficient to keep a large quantity of solid and liquid particles suspended within it. Although visible dust sometimes clouds the sky, these relatively large particles are too heavy to stay in the air very long. Many other particles are microscopic and remain suspended for considerable periods of time. They may originate from many sources, both natural and human made, and include sea salts from breaking waves, fine soil blown into the air, smoke and soot from fires, pollen and microorganisms lifted by the wind, ash and dust from volcanic eruptions, and more (**FIGURE 16.6A**). Collectively, these tiny solid and liquid particles are called **aerosols**.

From a meteorological standpoint, these tiny, often invisible particles can be significant. First, many act as surfaces on which water vapor can condense, an important function in the formation of clouds and fog. Second, aerosols can absorb, reflect, and scatter incoming solar radiation. Thus, when an air-pollution episode is occurring or when ash fills the sky following a volcanic eruption, the amount of sunlight reaching Earth's surface can be measurably reduced. Finally, aerosols contribute to an optical phenomenon we have all observed—the varied hues of red and orange at sunrise and sunset (**FIGURE 16.6B**).

Ozone Another important component of the atmosphere is **ozone**. It is a form of oxygen that combines three oxygen atoms into each molecule (O_3). Ozone is not the same as oxygen we breathe, which has two atoms per molecule (O_2). There is very little ozone in the atmosphere, and its distribution is not uniform. It is concentrated between 10 and 50 kilometers (6 and 31 miles) above the surface, in a layer called the *stratosphere*.

In this altitude range, oxygen molecules (O_2) are split into single atoms of oxygen (O) when they absorb ultraviolet radiation emitted by the Sun. Ozone is then created when a single atom of oxygen (O) and a molecule of oxygen (O_2) collide. This must happen in the presence of a third, neutral molecule that acts as a *catalyst* by allowing the reaction to take place without itself being consumed in the process. Ozone is concentrated in the 10- to 50-kilometer height

RE 16.6 Aerosols
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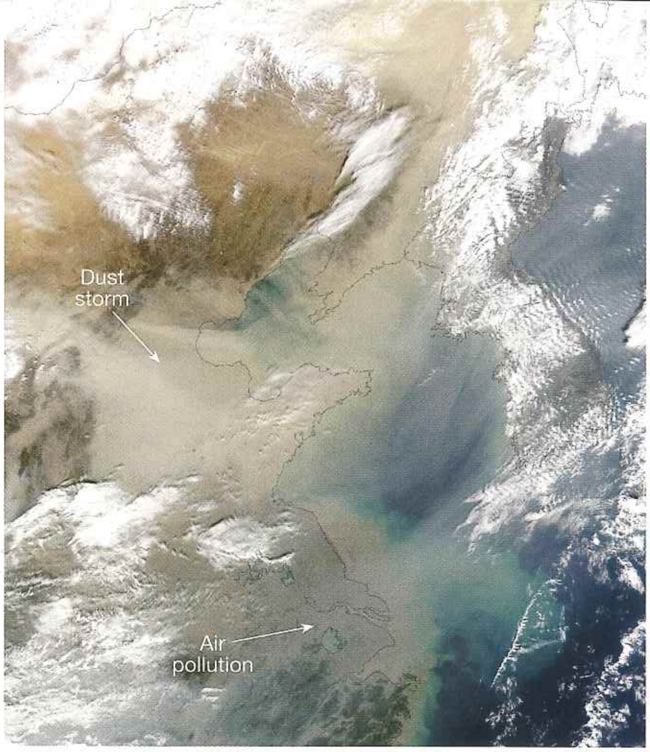

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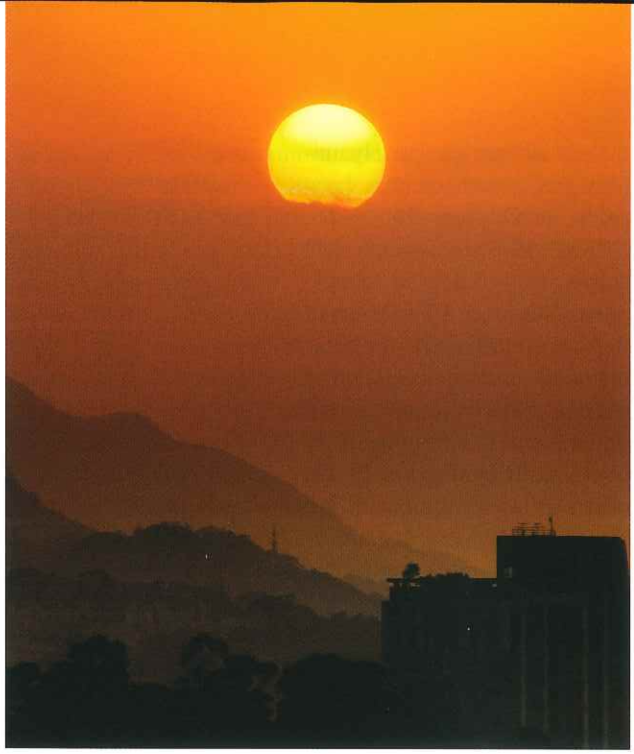


B.

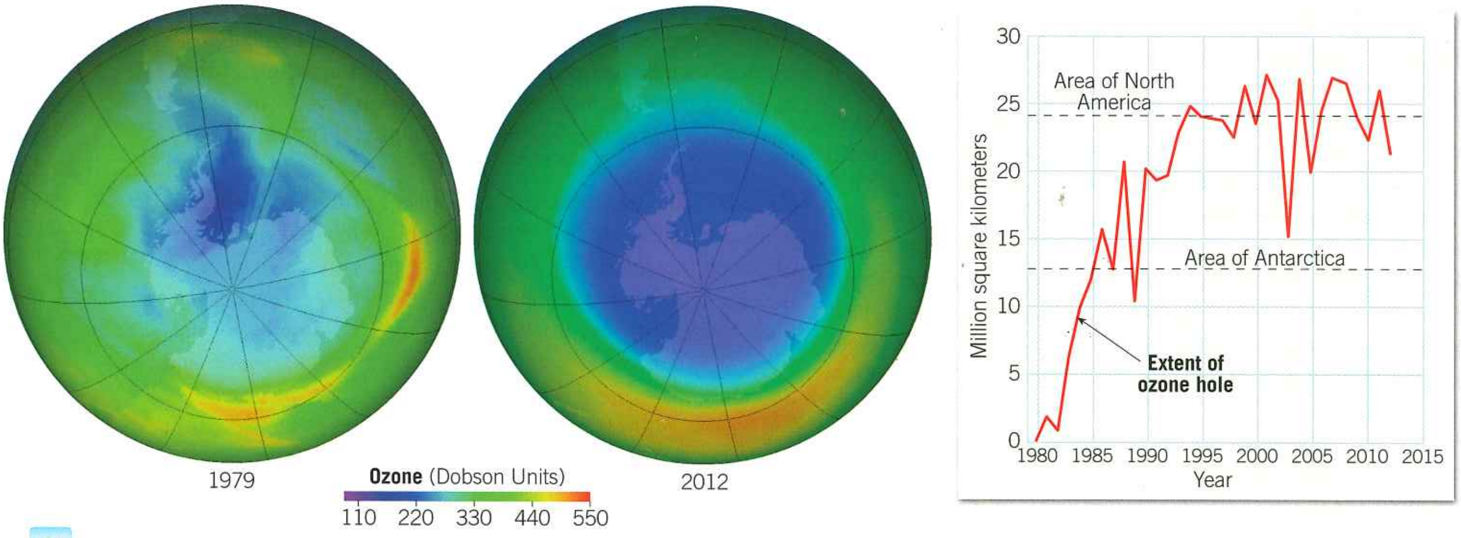
range because a crucial balance exists there: The ultraviolet radiation from the Sun is sufficient to produce single atoms of oxygen, and there are enough gas molecules to bring about the required collisions.

The presence of the ozone layer in our atmosphere is crucial to those of us who dwell on Earth. The reason is that ozone absorbs much of the potentially harmful ultraviolet (UV) radiation from the Sun. If ozone did not filter a great deal of the ultraviolet radiation, and if the Sun's UV rays reached the surface of Earth undiminished, our planet would be uninhabitable for most life as we know it. Thus, anything that reduces the amount of ozone in the atmosphere could affect the well-being of life on Earth. Just such a problem exists and is described in the next section.

Ozone Depletion: A Global Issue

Although stratospheric ozone is 10 to 50 kilometers (6 to 31 miles) above Earth's surface, it is vulnerable to human activities. Chemicals produced by people are breaking up ozone molecules in the stratosphere, weakening our shield against UV rays. This loss of ozone is a serious global-scale environmental problem. Measurements over the past three decades confirm that ozone depletion is occurring worldwide and is especially pronounced above Earth's poles. You can see this effect over the South Pole in **FIGURE 16.7**.

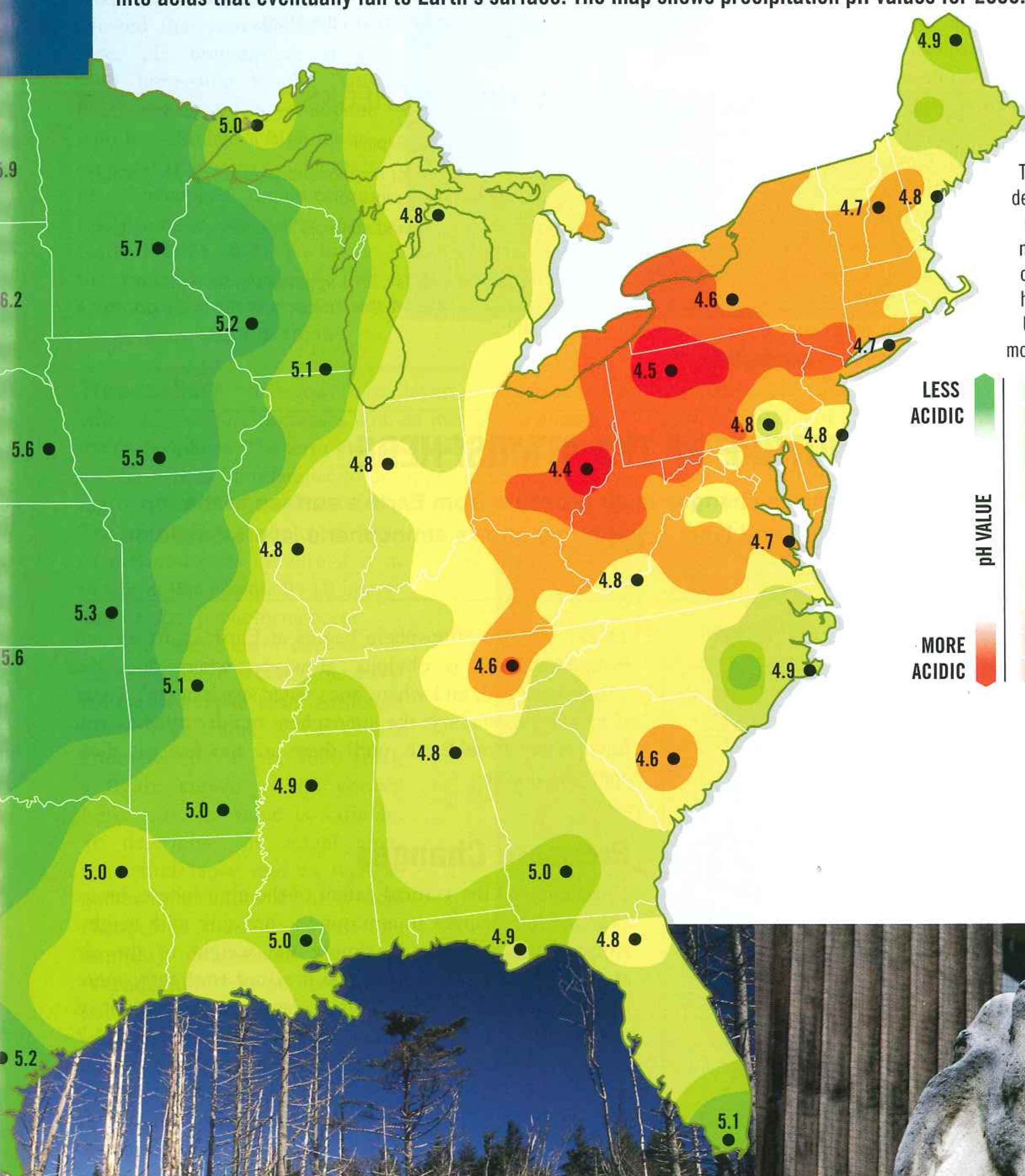
Over the past 60 years, people have unintentionally placed the ozone layer in jeopardy by polluting the



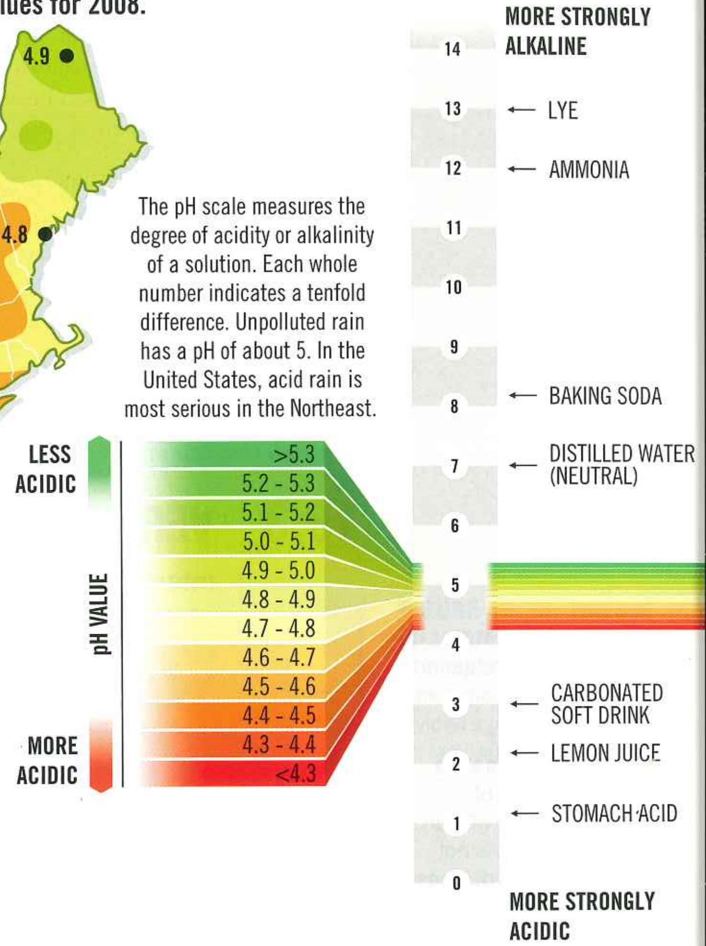
SmartFigure 16.7 Antarctic Ozone Hole The two satellite images show ozone distribution in the Southern Hemisphere on the days in September 1979 and 2012 when the ozone hole was largest. The dark blue shades over Antarctica correspond to the region with the sparsest ozone. The ozone hole is not technically a "hole" where no ozone is present but is actually a region of exceptionally depleted ozone in the stratosphere over the Antarctic that occurs in the spring. The small graph traces changes in the maximum size of the ozone hole, 1980 to 2012. (NASA)

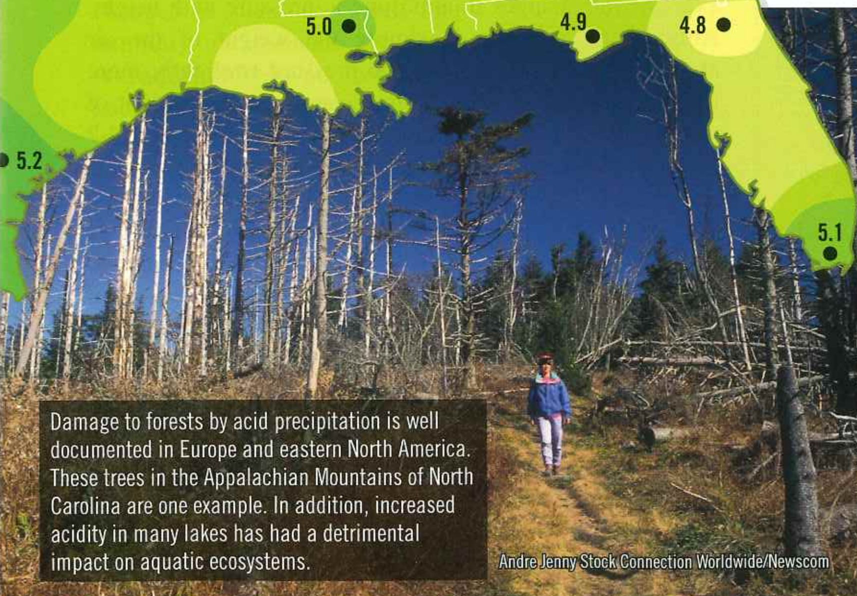
Acid Precipitation
A Human Impact on the Earth System

As a consequence of burning large quantities of coal and petroleum, tens of millions of tons of sulfur dioxide and nitrogen oxides enter the atmosphere each year. Through a series of complex chemical reactions, these pollutants are converted into acids that eventually fall to Earth's surface. The map shows precipitation pH values for 2008.



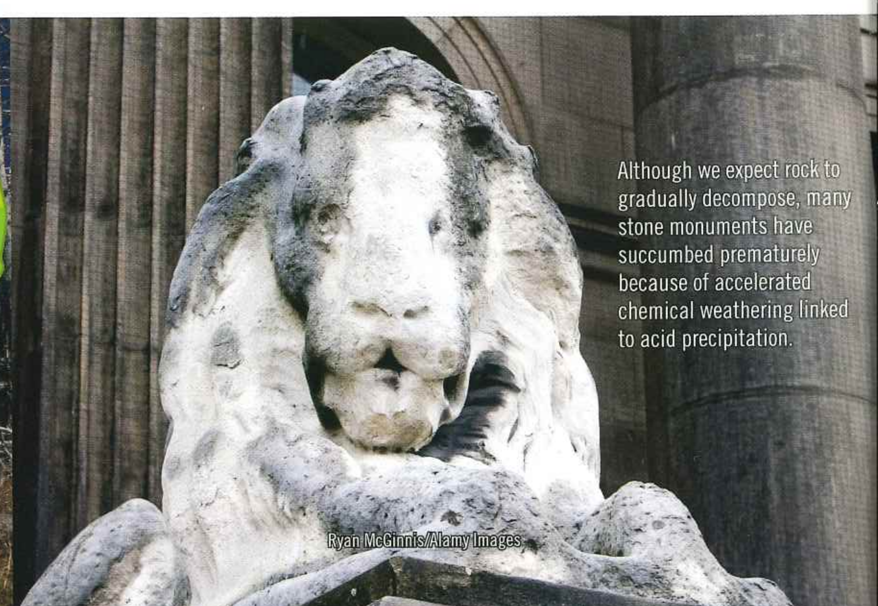
The pH scale measures the degree of acidity or alkalinity of a solution. Each whole number indicates a tenfold difference. Unpolluted rain has a pH of about 5. In the United States, acid rain is most serious in the Northeast.





Damage to forests by acid precipitation is well documented in Europe and eastern North America. These trees in the Appalachian Mountains of North Carolina are one example. In addition, increased acidity in many lakes has had a detrimental impact on aquatic ecosystems.

Andre Jenny Stock Connection Worldwide/Newscom



Although we expect rock to gradually decompose, many stone monuments have succumbed prematurely because of accelerated chemical weathering linked to acid precipitation.

Ryan McGinnis/Alamy Images

atmosphere. The most significant of the offending chemicals are known as *chlorofluorocarbons* (CFCs for short). Over the decades, many uses were developed for CFCs: They were used as coolants for air-conditioning and refrigeration equipment, cleaning solvents for electronic components, and propellants for aerosol sprays, and they were used in the production of certain plastic foams.

Because CFCs are practically inert (that is, not chemically active) in the lower atmosphere, some of these gases gradually make their way to the ozone layer, where sunlight separates the chemicals into their constituent atoms. The chlorine atoms released this way break up some of the ozone molecules.

Because ozone filters out most of the UV radiation from the Sun, a decrease in its concentration permits more of these harmful wavelengths to reach Earth's surface. The most serious threat to human health is an increased risk of skin cancer. An increase in damaging UV radiation also can impair the human immune system as well as promote cataracts, a clouding of the eye lens that reduces vision and may cause blindness if not treated.

In response to this problem, an international agreement known as the *Montreal Protocol* was developed under the sponsorship of the United Nations to eliminate the production and use of CFCs. More than 180 nations eventually ratified the treaty. Although relatively strong action has been taken, CFC levels in the atmosphere will not drop rapidly. Once in the atmosphere, CFC molecules can take many years to reach the ozone layer, and once there, they can remain active for decades. This does not promise a near-term reprieve for the ozone layer. Between 2060 and 2075, the abundance of ozone-depleting gases is projected to fall to values that existed before the ozone hole began to form in the 1980s.

16.2 CONCEPT CHECKS

1. Is *air* a specific gas? Explain.
2. What are the two major components of clean, dry air? What proportion does each represent?
3. Why are water vapor and aerosols important constituents of Earth's atmosphere?
4. What is ozone? Why is ozone important to life on Earth? What are CFCs, and what is their connection to the ozone problem?

16.3 VERTICAL STRUCTURE OF THE ATMOSPHERE

Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows atmospheric layers based on temperature.

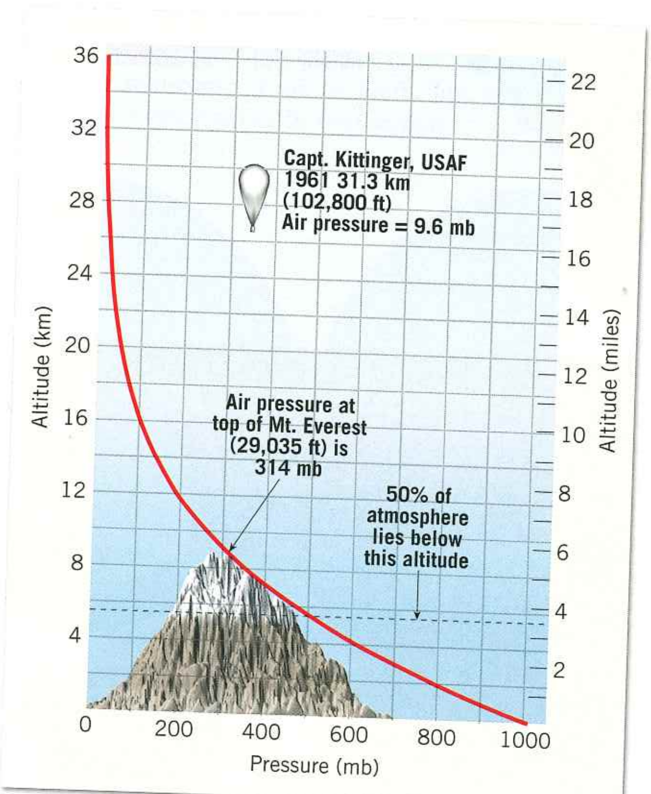


FIGURE 16.8 Air Pressure Changes with Altitude The rate of pressure decrease with an increase in altitude is not constant. Pressure decreases rapidly near Earth's surface and more gradually at greater heights. Put another way, the graph shows that the vast bulk of the gases making up the atmosphere is very near Earth's surface and that the gases gradually merge with the emptiness of space.

To say that the atmosphere begins at Earth's surface and extends upward is obvious. However, where does the atmosphere end, and where does outer space begin? There is no sharp boundary; the atmosphere rapidly 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, let us examine the 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 (mb). This corresponds to a weight of slightly more than 1 kilogram per square centimeter (14.7 pounds per square inch). The pressure at higher altitudes is less (**FIGURE 16.8**).

One-half of the atmosphere lies below an altitude of 5.6 kilometers (3.5 miles). At about 16 kilometers (10 miles), 90 percent of the atmosphere has been traversed, and above 100 kilometers (62 miles), only 0.00003 percent of all the gases making up the atmosphere remains. Even so, traces of our atmosphere extend far beyond this altitude, gradually merging with the emptiness of space.

Temperature Changes

By the early twentieth century, much had been learned about the lower atmosphere. The upper atmosphere was partly known from indirect methods. Data from balloons and kites showed that near Earth's surface, air temperature drops with increasing height. This phenomenon is felt by anyone who has climbed a high mountain and is obvious in pictures of snowcapped mountaintops rising above snow-free lowlands (**FIGURE 16.9**). We divide the atmosphere vertically into four layers, on the basis of temperature (**FIGURE 16.10**).

FIGURE 16.9 Temperatures Drop with an Increase in Altitude in the Troposphere Snow-capped mountains and snow-free lowlands are a reminder that temperatures decrease as we go higher in the troposphere. (Photo by David Wall/Alamy)

Troposphere The lowermost layer in which we live, where temperature decreases with an increase in altitude, is the **troposphere**. The term literally means the region where air "turns over," a reference to the appreciable vertical mixing of air in this lowermost zone. The troposphere is the chief focus of meteorologists because it is in this layer that essentially all important weather phenomena occur.

The temperature decrease in the troposphere is called the **environmental lapse rate**. Although its average value is 6.5°C per kilometer (3.5°F per 1000 feet), a figure known as the *normal lapse rate*, its value is variable. To determine the actual environmental lapse rate as well as gather information about vertical changes in pressure, wind, and humidity, radiosondes are used. A **radiosonde** is an instrument package that is attached to a balloon and transmits data by radio as it ascends through the atmosphere (**FIGURE 16.11**).

The thickness of the troposphere is not the same everywhere; it varies with latitude and season. On average, the temperature drop continues to a height of about 12 kilometers (7.4 miles). The outer boundary of the troposphere is the *tropopause*.

Stratosphere Beyond the tropopause is the **stratosphere**. In the stratosphere, the temperature remains constant to a height of about 20 kilometers (12 miles) and then begins a gradual increase that continues until the *stratopause*, at a height of nearly 50 kilometers (30 miles) above

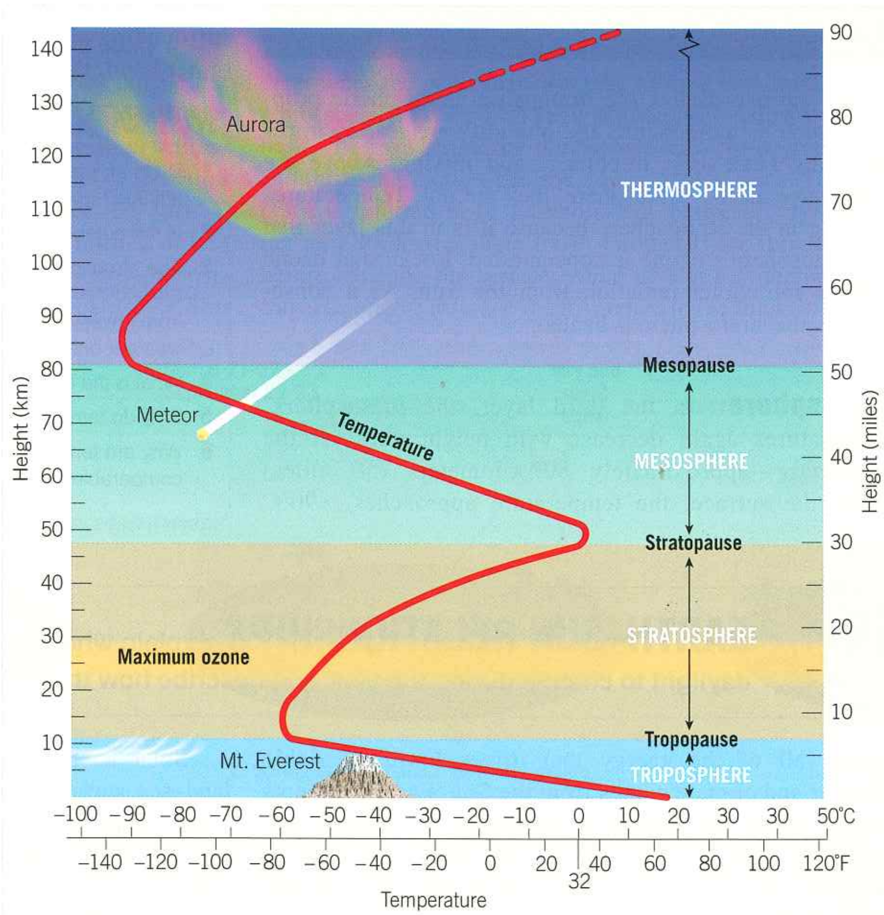


FIGURE 16.10 Thermal Structure of the Atmosphere Earth's atmosphere is traditionally divided into four layers, based on temperature.

IGURE 16.11
adiosonde A radiosonde s a lightweight package of nstruments that is carried loft by a small weather alloon. It transmits data n vertical changes in emperature, pressure, and umidity in the troposphere. he troposphere is where ractically all weather henomena occur, so it s very important to have equent measurements. Photo by David R. Frazier/Danita elimont/Newscom)

Earth's surface. Below the tropopause, atmospheric properties such as temperature and humidity are readily transferred by large-scale turbulence and mixing. Above the tropopause, in the stratosphere, they are not. Temperatures increase in the stratosphere because it is in this layer that the atmosphere's ozone is concentrated. Recall that ozone absorbs ultraviolet radiation from the Sun. As a consequence, the stratosphere is heated.

Mesosphere In the third layer, the **mesosphere**, temperatures again decrease with height until, at the *mesopause*—approximately 80 kilometers (50 miles) above the surface, the temperature approaches −90°C (−130°F). The coldest temperatures anywhere in the atmosphere occur at the mesopause. Because accessibility is difficult, the mesosphere is one of the least explored regions of the atmosphere. It cannot be reached by the highest research balloons, nor is it accessible to the lowest orbiting satellites. Recent technological developments are just beginning to fill this knowledge gap.

Thermosphere 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. In the extremely rarefied air of this outermost layer, temperatures again increase, due to the absorption of very short-wave, high-energy solar radiation by atoms of oxygen and nitrogen.

Temperatures rise to extremely high values of more than 1000°C (1800°F) in the thermosphere. But such temperatures are not comparable to those experienced near Earth's surface. Temperature is defined in terms of the average speed at which molecules move. Because the gases of the thermosphere are moving at very high speeds, the temperature is very high. But the gases are so sparse that, collectively, they possess only an insignificant quantity of heat. For this reason, the temperature of a satellite orbiting Earth in the thermosphere is determined chiefly by the amount of solar radiation it absorbs and not by the high temperature of the almost nonexistent surrounding air. If an astronaut inside were to expose his or her hand, the atmosphere would not feel hot.

16.3 CONCEPT CHECKS

1. Does air pressure increase or decrease with an increase in altitude? Is the rate of change constant or variable? Explain.
2. Is the outer edge of the atmosphere clearly defined? Explain.
3. The atmosphere is divided vertically into four layers, on the basis of temperature. List and describe these layers in order, from lowest to highest. In which layer does practically all our weather occur?
4. What is the environmental lapse rate, and how is it determined?
5. Why do temperatures increase in the stratosphere?
6. Why are temperatures in the thermosphere not strictly comparable to those experienced near Earth's surface?

16.4 EARTH–SUN RELATIONSHIPS

Explain what causes the Sun angle and length of daylight to change during the year and describe how these changes produce the seasons.

Nearly all of the energy that drives Earth's variable weather and climate comes from the Sun. Earth intercepts only a minute percentage of the energy given off by the Sun—less than 1 two-billionth. This may seem to be an insignificant amount, until we realize that it is several hundred thousand times the electrical-generating capacity of the United States.

Solar energy is not distributed evenly over Earth's land–sea surface. The amount of energy received varies with latitude, time of day, and season of the year. Contrasting images of polar bears on ice rafts and palm trees along a remote tropical beach serve to illustrate the extremes. It is the unequal heating of Earth that creates winds and drives the ocean's currents. These movements of air and water, in turn, transport heat from the tropics toward the poles, in an unending attempt to balance energy inequalities. The consequences of these processes are the phenomena we call weather.

If the Sun were "turned off," global winds and ocean currents would quickly cease. Yet as long as the Sun shines, the winds *will* blow and weather *will* persist. So to understand how the atmosphere's dynamic weather machine works, we must first know why different latitudes receive varying quantities of solar energy and why the amount of solar energy changes to produce the seasons. 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–sea surface.

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 poles. Our planet rotates once every 24 hours, producing the daily cycle of daylight and darkness. At any moment, half of Earth is experiencing daylight and the other half darkness. The line separating the dark half of Earth from the lighted half is called the **circle of illumination**.

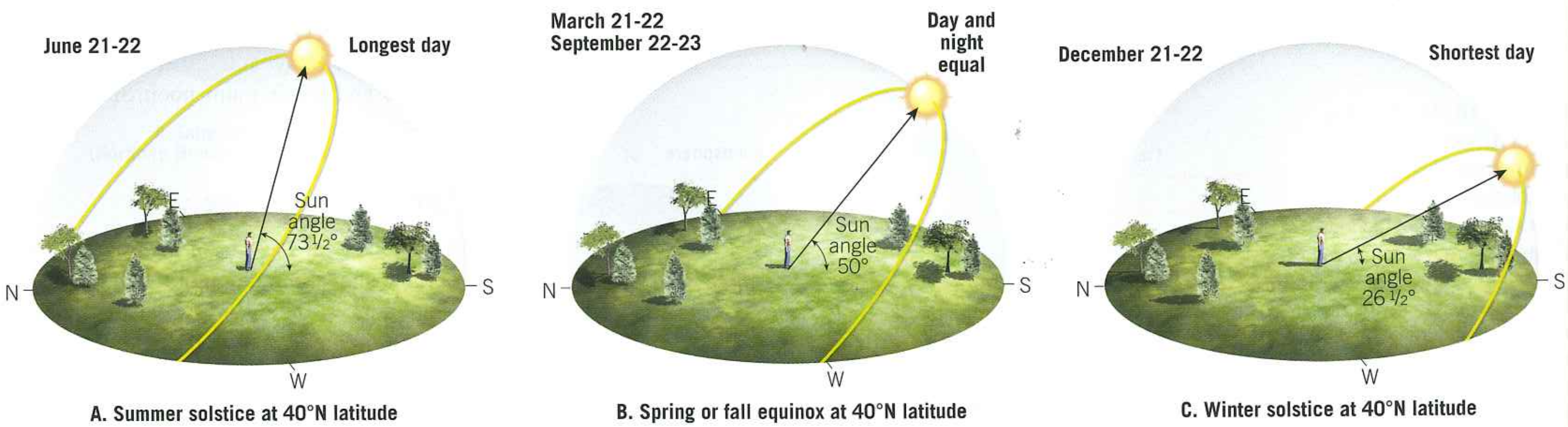
Revolution refers to the movement of Earth in a slightly elliptical orbit around the Sun. The distance between Earth and Sun averages about 150 million kilometers (93 million miles). Because Earth's orbit is not perfectly circular, however, the distance varies during the course of a year. Each year, on about January 3, our planet is about 147.3 million kilometers (91.5 million miles) from the Sun, closer than at any other time—a position known as *perihelion*. About 6 months later, on July 4, Earth is about 152 million kilometers (94.5 million miles) from the Sun, farther away than at any other time—a position called *aphelion*. Although Earth is closest to the Sun and receives up to 7 percent more energy in January than in July, this difference plays only a minor role in producing seasonal temperature variations, as evidenced by the fact that Earth is closest to the Sun during the Northern Hemisphere winter.

What Causes the Seasons?

If variations in the distance between the Sun and Earth are not responsible for seasonal temperature changes, what is? The gradual but significant change in the length of daylight certainly accounts for some of the difference we notice between summer and winter. Furthermore, a gradual change in the angle (altitude) of the Sun above the horizon is also a contributing factor (**FIGURE 16.12**). For example, someone living in Chicago, Illinois, experiences the noon Sun highest in the sky in late June. But as summer gives way to autumn, the noon Sun appears lower in the sky, and sunset occurs earlier each evening.

The seasonal variation in the angle of the Sun above the horizon affects the amount of energy received at Earth's surface in two ways. First, when the Sun is directly overhead (at a 90-degree angle), the solar rays are most concentrated and thus most intense (**FIGURE 16.13A**). The lower the angle, the more spread out and less intense is the solar radiation that reaches the surface (**FIGURE 16.13B,C**). To illustrate this principle, hold a flashlight at a right angle to a surface and then change the angle.

Second, but of lesser importance, the angle of the Sun determines the path solar rays take as they pass through the atmosphere (**FIGURE 16.14**). When the Sun is directly overhead, the rays strike the atmosphere at a 90-degree angle and travel the shortest possible route to the surface. This distance is referred to as *1 atmosphere*. However, rays entering at a 30-degree angle travel through twice this distance before reaching the surface, while rays at a 5-degree angle travel through a distance roughly equal to the thickness of 11



SmartFigure 16.12 The Changing Sun Angle Daily paths of the Sun for a place located at 40° north latitude for **A.** summer solstice, **B.** spring or fall equinox, and **C.** winter solstice. As we move from summer to winter, the angle of the noon Sun decreases from 73½ to 26½ degrees—a difference of 47 degrees. Notice also how the location of sunrise (east) and sunset (west) changes during a year.

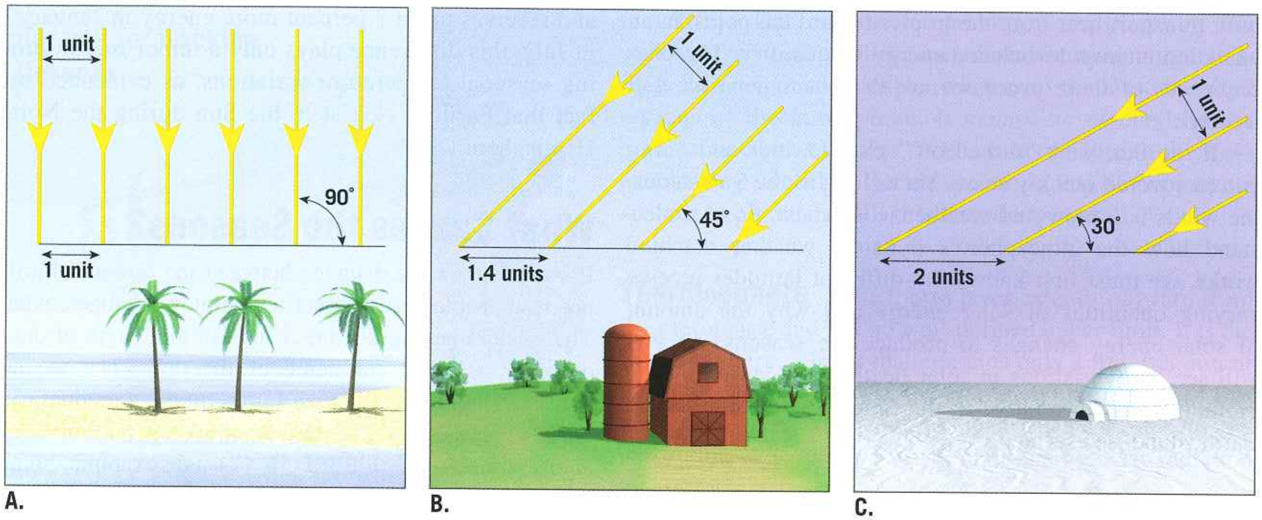


FIGURE 16.13 The Sun Angle Influences the Intensity of Solar Radiation at Earth's Surface Changes in the Sun's angle cause variations in the amount of solar energy reaching Earth's surface. The nearer the angle to 90 degrees, the more intense the solar radiation.

atmospheres. The longer the path, the greater the chance that sunlight will be dispersed by the atmosphere, which reduces the intensity at the surface. These conditions account for the fact that we cannot look directly at the midday Sun, but we can enjoy gazing at a sunset.

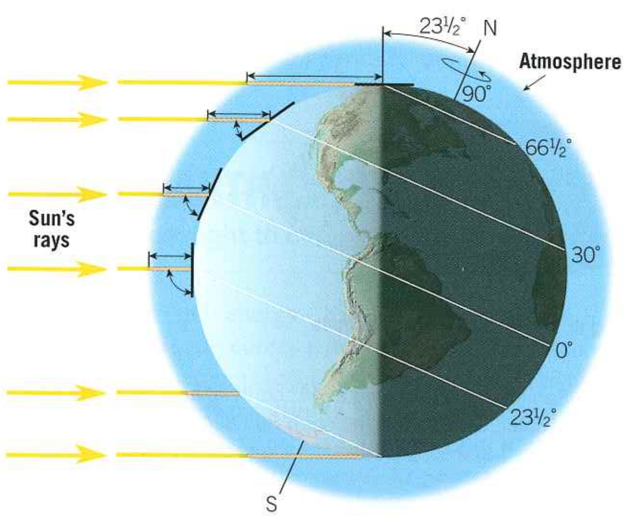
It is important to remember that Earth's shape is spherical. On any given day, the only places that will receive vertical (90-degree) rays from the Sun are located along one particular line of latitude. As we move either north or south of this location, the Sun's rays strike at ever-decreasing angles. The nearer a place is to the latitude receiving vertical rays of the Sun, the higher will be its noon Sun and the more concentrated will be the radiation it receives (see Figure 16.14).

Earth's Orientation

What causes fluctuations in Sun angle and length of daylight that occur during the course of a year? Variations occur because Earth's orientation to the Sun continually changes as it travels along its orbit. Earth's axis (the imaginary line through the poles around which Earth rotates) is not perpendicular to the plane of its orbit around the Sun. Instead, it is tilted 23½ degrees from the perpendicular, as shown in **FIGURE 16.15**. This is called the **inclination of the axis**. If the axis were not inclined, Earth would lack seasons. Because the axis remains pointed in the same direction (toward the North Star), the orientation of Earth's axis to the Sun's rays is constantly changing (see Figure 16.15).

For example, on one day in June each year, the axis is such that the Northern Hemisphere is "leaning" 23½ degrees *toward* the Sun (see Figure 16.15, left). Six months later, in December, when Earth has moved to the opposite side of its orbit, the Northern Hemisphere "leans" 23½ degrees *away* from the Sun (see Figure 16.15, right). On days between these extremes, Earth's axis is leaning at amounts less than 23½ degrees to the rays of the Sun. This change in orientation causes the spot where the Sun's rays are vertical to make an annual migration from 23½ degrees north of the equator to 23½ degrees south of the equator.

In turn, this migration causes the angle of the noon Sun to vary by up to 47° (23½° + 23½°) for many locations during the year. For example, a midlatitude city like New York (about 40° north latitude) has a maximum noon Sun angle of 73½° when the Sun's vertical rays reach their farthest northward location in June and a minimum noon Sun angle of 26½° 6 months later.



IGURE 16.14 The Sun ngle Affects the Path f Sunlight Through the tmosphere Notice that ays striking Earth at a low ngle (toward the poles) must avel through more of the tmosphere than rays striking t a high angle (around e equator) and are thus ubject to greater depletion y reflection, scattering, and bsorption.

Solstices and Equinoxes

Historically, 4 days each year have been given special significance, based on the annual migration of the direct rays of the Sun and its importance to the yearly weather cycle. On June 21 or 22, Earth is in a position such that the north end of its axis is tilted 23½° *toward* the Sun (**FIGURE 16.16A**). At this time, the vertical rays of the Sun strike 23½° north latitude (23½° north of the equator), a latitude known as the **Tropic of Cancer**. For people in the Northern Hemisphere, June 21 or 22 is known as the **summer solstice**, the first "official" day of summer.

Six months later, on about December 21 or 22, Earth is in the opposite position, with the Sun's vertical rays

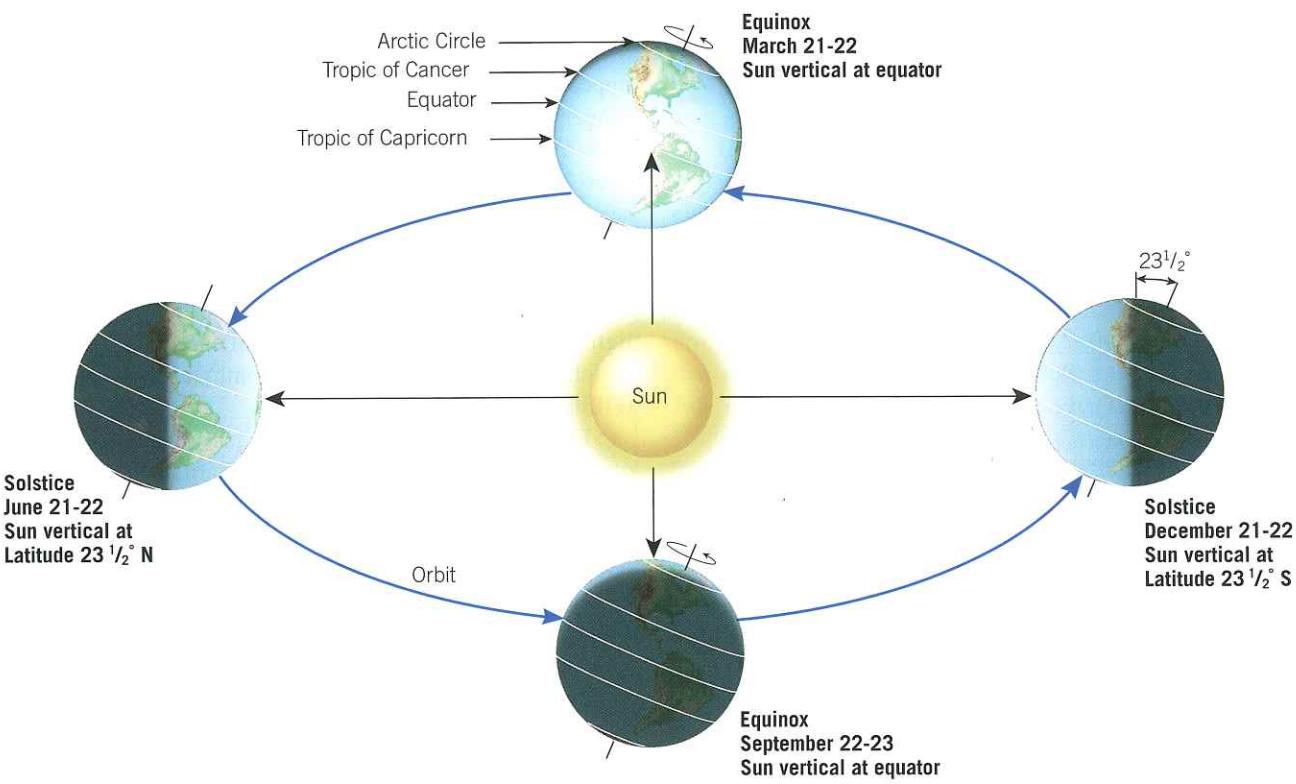
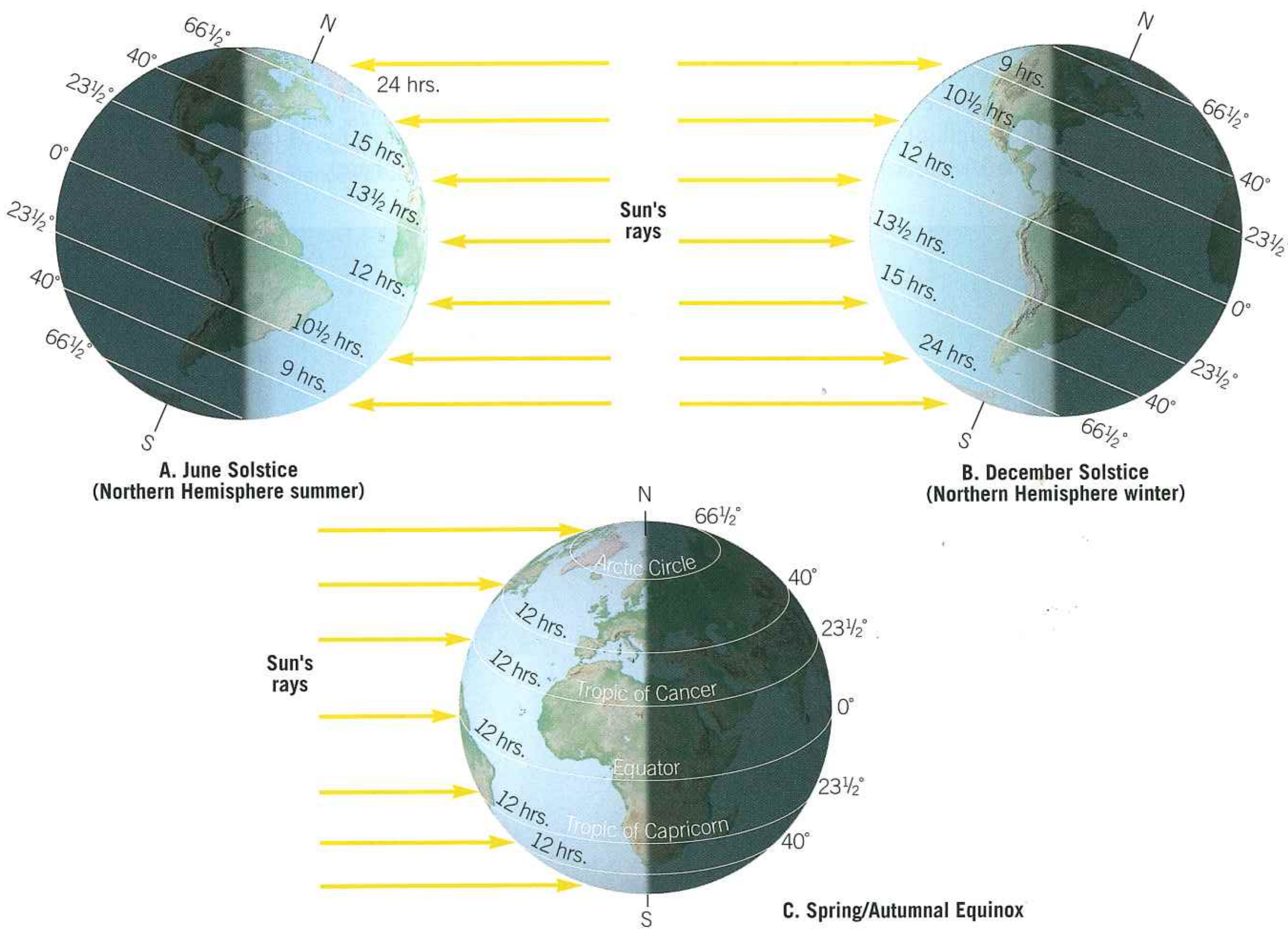


FIGURE 16.15 Earth–Sun Relationships



SmartFigure 16.16 Characteristics of the Solstices and Equinoxes

TABLE 16.1 Length of Daylight

Latitude (degrees)	Summer Solstice	Winter Solstice	Equinoxes
0	12 h	12 h	12 h
10	12 h 35 min	11 h 25 min	12 h
20	13 h 12 min	10 h 48 min	12 h
30	13 h 56 min	10 h 04 min	12 h
40	14 h 52 min	9 h 08 min	12 h
50	16 h 18 min	7 h 42 min	12 h
60	18 h 27 min	5 h 33 min	12 h
70	24 h (for 2 mo)	0 h 00 min	12 h
80	24 h (for 4 mo)	0 h 00 min	12 h
90	24 h (for 6 mo)	0 h 00 min	12 h

striking at 23½° south latitude (**FIGURE 16.16B**). This parallel is known as the **Tropic of Capricorn**. For those in the Northern Hemisphere, December 21 and 22 is the **winter solstice**. However, at the same time in the Southern Hemisphere, people are experiencing just the opposite—the summer solstice.

Midway between the solstices are the equinoxes. September 22 or 23 is the date of the **autumnal (fall) equinox** in the Northern Hemisphere, and March 21 or 22 is the date of the **spring equinox**. On these dates, the vertical rays of the Sun strike the equator (0° latitude) because Earth is in such a position in its orbit that the axis is tilted neither toward nor away from the Sun (**FIGURE 16.16C**).

The length of daylight versus darkness is also determined by Earth's position in orbit. The length of daylight on June 21, the summer solstice in the Northern Hemisphere, is greater than the length of night. This fact can be established from Figure 16.16A by comparing the fraction of a given latitude that is on the "day" side of the circle of illumination with the fraction on the "night" side. The opposite is true for the winter solstice, when the nights are longer than the days. Again for comparison, let us consider New York City, which has about 15 hours of daylight on June 21 and only about 9 hours on December 21. (You can see this in Figure 16.16 and **TABLE 16.1**.) Also note from Table 16.1 that the farther north of the equator you are on June 21, the longer the period of daylight. When you reach the Arctic Circle (66½° north latitude), the length of daylight is 24 hours. This is the land of the "midnight Sun," which does not set for about 6 months at the North Pole (**FIGURE 16.17**).

During an equinox (meaning "equal night"), the length of daylight is 12 hours *everywhere* on Earth, because the circle of illumination passes directly through the poles, dividing the latitudes in half (see Figure 16.16C).

As a review of the characteristics of the summer solstice for the Northern Hemisphere, examine Figure 16.16A and Table 16.1 and consider the following facts:

- The solstice occurs on June 21 or 22.
- The vertical rays of the Sun are striking the Tropic of Cancer (23½° north latitude).
- Locations in the Northern Hemisphere are experiencing their greatest length of daylight (opposite for the Southern Hemisphere).
- Locations north of the Tropic of Cancer are experiencing their highest noon Sun angles (opposite for places south of the Tropic of Capricorn).
- The farther you are north of the equator, the longer the period of daylight, until the Arctic Circle is reached, where daylight lasts for 24 hours (opposite for the Southern Hemisphere).

IGURE 16.17 Midnight un Multiple exposures f the Sun, representative f midsummer in the high titudes. This example hows the midnight Sun in orway. (Photo by Martin Woike/ GE Fotostock)

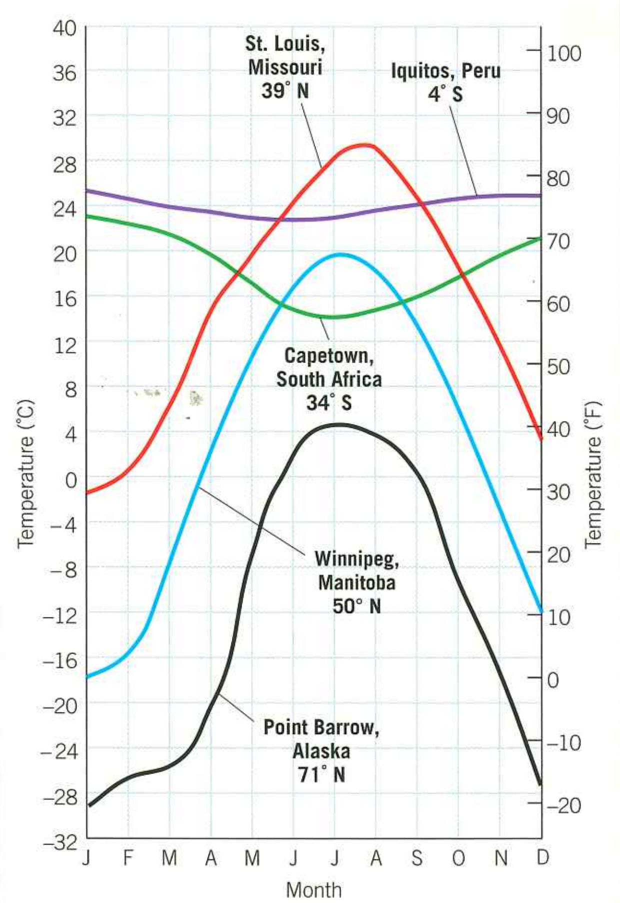


FIGURE 16.18 Monthly Temperatures for Cities at Different Latitudes Places located at higher latitudes experience larger temperature differences between summer and winter. Note that Cape Town, South Africa, experiences winter in June, July, and August.

The facts about the winter solstice are just the opposite. It should now be apparent why a midlatitude location is warmest in the summer, for it is then that days are longest and Sun's altitude is highest.

These seasonal changes, in turn, cause the month-to-month variations in temperature observed at most locations outside the tropics. **FIGURE 16.18** shows mean monthly temperatures for selected cities at different latitudes. Notice that the cities located at more poleward latitudes experience larger temperature differences from summer to winter than do cities located nearer the equator. Also notice that temperature minimums for Southern Hemisphere locations occur in July, whereas they occur in January for most places in the Northern Hemisphere.

All places at the same latitude have identical Sun angles and lengths of daylight. If the Earth–Sun relationships just described were the only controls of temperature, we would expect these places to have identical temperatures as well. Obviously, this is not the case. Other factors that influence temperature are discussed later in the chapter.

16.4 CONCEPT CHECKS

1. Do the annual variations in Earth–Sun distance adequately account for seasonal temperature changes? Explain.
2. Create a simple sketch to show why the intensity of solar radiation striking Earth's surface changes when the Sun angle changes.
3. Briefly explain the primary cause of the seasons.
4. What is the significance of the Tropic of Cancer and the Tropic of Capricorn?
5. After examining Table 16.1, write a general statement that relates the season, latitude, and the length of daylight.

EYE ON EARTH

This image shows the first sunrise of 2008 at Amundsen-Scott Station, a research facility at the South Pole. At the moment the Sun cleared the horizon, the weathered American flag was seen whipping in the wind above a sign marking the location of the geographic South Pole. (NASA)

QUESTION 1 *What was the approximate date that this photograph was taken?*

QUESTION 2 *How long after this photo was taken did the Sun set at the South Pole?*

QUESTION 3 *On what date would you expect Amundsen-Scott Station to experience its highest noon Sun angle? Explain.*

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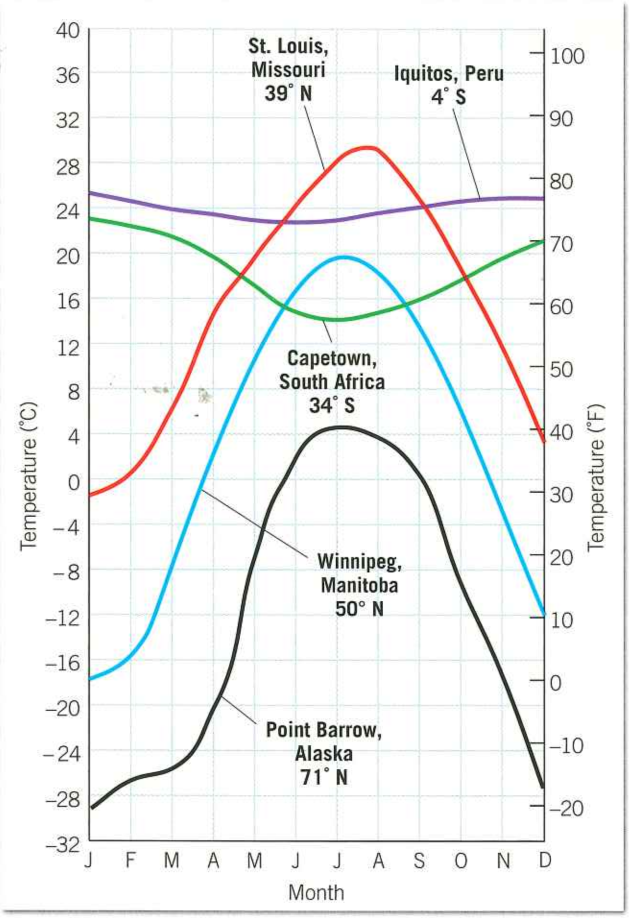
FIGURE 16.17 Midnight Sun Multiple exposures of the Sun, representative of midsummer in the high latitudes. This example shows the midnight Sun in Norway. (Photo by Martin Woike/AGE Fotostock)



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EYE ON EARTH

This image shows the first sunrise of 2008 at Amundsen-Scott Station, a research facility at the South Pole. At the moment the Sun cleared the horizon, the weathered American flag was seen whipping in the wind above a sign marking the location of the geographic South Pole. (NASA)

QUESTION 1 *What was the approximate date that this photograph was taken?*

QUESTION 2 *How long after this photo was taken did the Sun set at the South Pole?*

QUESTION 3 *On what date would you expect Amundsen-Scott Station to experience its highest noon Sun angle? Explain.*

16.5 ENERGY, HEAT, AND TEMPERATURE

Distinguish between heat and temperature. List and describe the three mechanisms of heat transfer.

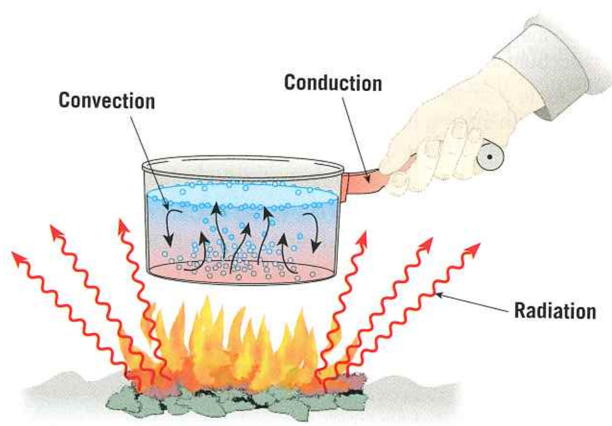
The universe is made up of a combination of matter and energy. The concept of matter is easy to grasp because it is the "stuff" we can see, smell, and touch. Energy, on the other hand, is abstract and therefore more difficult to describe. For our purposes, we define energy simply as *the capacity to do work*. We can think of work as being accomplished whenever matter is moved. You are likely familiar with some of the common forms of energy, such as thermal, chemical, nuclear, radiant (light), and gravitational energy. One type of energy is described as *kinetic energy*, which is energy of motion. Recall that matter is composed of atoms or molecules that are constantly in motion and therefore possesses kinetic energy.

Heat is a term that is commonly used synonymously with *thermal energy*. In this usage, heat is energy possessed by a material arising from the internal motions of its atoms or molecules. Whenever a substance is heated, its atoms move faster and faster, which leads to an increase in its heat content. **Temperature**, on the other hand, is related to the average kinetic energy of a material's atoms or molecules. Stated another way, the term *heat* generally refers to the quantity of energy present, whereas the word *temperature* refers to the intensity—that is, the degree of "hotness."

Heat and temperature are closely related concepts. Heat is the energy that flows because of temperature differences. In all situations, *heat is transferred from warmer to cooler objects*. Thus, if two objects of different temperature are in contact, the warmer object will become cooler and the cooler object will become warmer until they both reach the same temperature.

Three mechanisms of heat transfer are recognized: conduction, convection, and radiation. Although we present them separately, all three processes go on simultaneously in the atmosphere. In addition, these mechanisms operate to transfer heat between Earth's surface (both land and water) and the atmosphere.

SmartFigure 16.19
he Three Mechanisms of eat Transfer



Mechanism of Heat Transfer: Conduction

Conduction is familiar to all of us. Anyone who has touched a metal spoon that was left in a hot pan has discovered that heat was conducted through the spoon. **Conduction** is *the transfer of heat through matter by molecular activity*. The energy of molecules is transferred through collisions from one molecule to another, with the heat flowing from the higher temperature to the lower temperature.

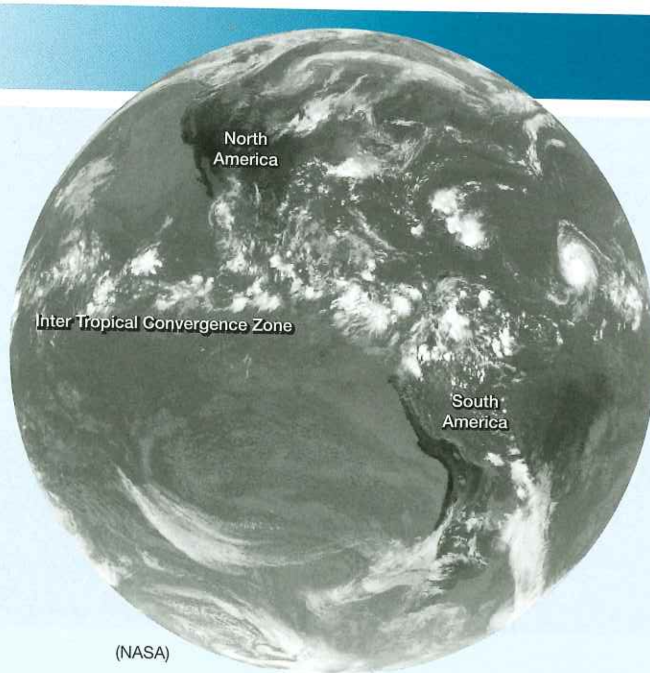
The ability of substances to conduct heat varies considerably. Metals are good conductors, as those of us who have touched hot metal have quickly learned (**FIGURE 16.19**). Air, conversely, is a very poor conductor of heat. Consequently,

EYE ON EARTH

This infrared (IR) image produced by the *GOES-14* satellite displays cold objects as bright white and hot objects as black. The hottest (blackest) features shown are land surfaces, and the coldest (whitest) features are the tops of towering storm clouds. Recall that we cannot see infrared (thermal) radiation, but we have developed instruments that are capable of extending our vision into the long-wavelength portion of the electromagnetic spectrum.

QUESTION 1 *Several areas of cloud development and potential storms are shown on this IR image. One is a well-developed tropical storm named Hurricane Bill. Can you locate this storm?*

QUESTION 2 *What is an advantage of IR images over visible images?*



(NASA)

conduction is important only between Earth's surface and the air directly in contact with the surface. As a means of heat transfer for the atmosphere as a whole, conduction is the least significant.

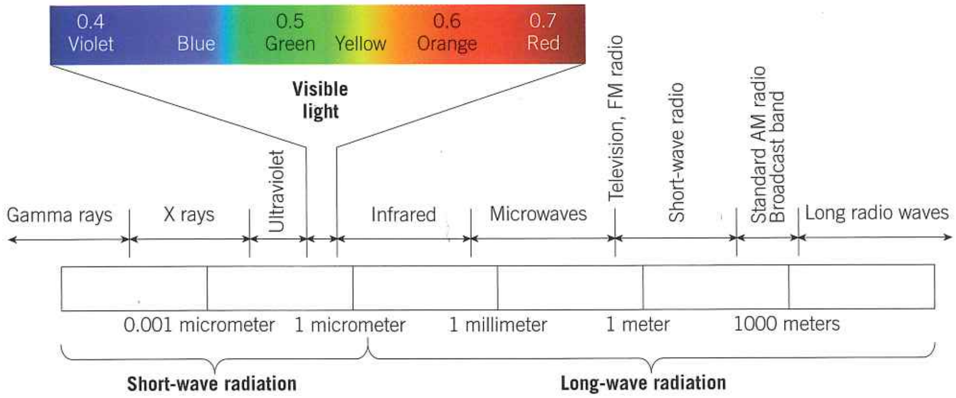


FIGURE 16.20 The Electromagnetic Spectrum This diagram illustrates the wavelengths and names of various types of radiation. Visible light consists of an array of colors we commonly call the "colors of the rainbow."

Mechanism of Heat Transfer: Convection

Much of the heat transport that occurs in the atmosphere occurs via convection. **Convection** is *the transfer of heat by mass movement or circulation within a substance*. It takes place in fluids (e.g., liquids like the ocean and gases like air) where the atoms and molecules are free to move about.

The pan of water in Figure 16.19 illustrates the nature of simple convective circulation. 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. Because of this new buoyancy, the warmer water rises. 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—that is, from the bottom up—the water will continue to "turn over," producing a *convective circulation*. In a similar manner, most of the heat acquired in the lowest portion of the atmosphere by way of radiation and conduction is transferred by convective flow.

On a global scale, convection in the atmosphere creates a huge, worldwide air circulation. This is responsible for the redistribution of heat between hot equatorial regions and the frigid poles. This important process is discussed in detail in Chapter 18.


Dennis Tasa

Mechanism of Heat Transfer: Radiation

The third mechanism of heat transfer is **radiation**. As shown in Figure 16.19, radiation travels out in all directions from its source. Unlike conduction and convection, which need a medium to travel through, radiant energy readily travels through the vacuum of space. Thus, radiation is the heat-transfer mechanism by which solar energy reaches our planet.

Solar Radiation

From our everyday experience, we know that the Sun emits light and heat as well as the ultraviolet rays that cause suntan. Although these forms of energy comprise a major portion of the total energy that radiates from the Sun, they are only part of a large array of energy called radiation, or **electromagnetic radiation**. This array or spectrum of electromagnetic energy is shown in **FIGURE 16.20**. All radiation, whether x-rays, radio waves, or heat waves, travels through the vacuum of space at 300,000 kilometers (186,000 miles) per second and only slightly slower through our atmosphere.

Nineteenth-century physicists were so puzzled by the seemingly impossible phenomenon of energy traveling through the vacuum of space without a medium to transmit it that they assumed that a material, which they named *ether*, existed between the Sun and Earth. This medium was thought to transmit radiant energy in much the same way that air transmits sound waves. Of course, this was incorrect. We now know that, like gravity, radiation requires no material for transmission.

In some respects, the transmission of radiant energy parallels the motion of the gentle swells in the open ocean. Like ocean swells, electromagnetic waves come in various sizes. For our purpose, the most important characteristic is their *wavelength*, or the distance from one crest to the next. Radio waves have the longest wavelengths, ranging to tens of kilometers, whereas gamma waves are the shortest, being less than one-billionth of a centimeter long.

Visible light, as the name implies, is the only portion of the spectrum we can see. We often refer to visible light as "white" light because it appears "white" in color. However, it is easy to show that white light is really a mixture of colors, each corresponding to a specific wavelength. Using a prism, white light can be divided into the colors of the rainbow. Figure 16.20 shows that violet has the shortest wavelength—

0.4 micrometer (1 micrometer is 0.0001 centimeter)—and red has the longest wavelength—0.7 micrometer.

Located adjacent to red, and having a longer wavelength, is **infrared** radiation, which we cannot see but which we can detect as heat. The closest invisible waves to violet are called **ultraviolet (UV)** rays. They are responsible for the sunburn that can occur after intense exposure to the Sun. Although we divide radiant energy into groups based on our ability to perceive the different types, all forms of radiation are basically the same. When any form of radiant energy is absorbed by an object, the result is an increase in molecular motion, which causes a corresponding increase in temperature.

Laws of Radiation To obtain a better understanding of how the Sun's radiant energy interacts with Earth's atmosphere and land–sea surface, it is helpful to have a general understanding of the basic laws governing radiation:

- *All objects, at whatever temperature, emit radiant energy.* Thus, not only hot objects like the Sun but also Earth, including its polar ice caps, continually emit energy.
- *Hotter objects radiate more total energy per unit area than do colder objects.* The Sun, which has a surface temperature of nearly 6000°C (10,000°F), emits about 160,000 times more energy per unit area than does Earth, which has an average surface temperature of about 15°C (59°F).
- *Hotter objects radiate more energy in the form of short-wavelength radiation than do cooler objects.* We can visualize this law by imagining a piece of metal that, when heated sufficiently (as occurs in a blacksmith shop), produces a white glow. As the metal cools, it emits more of its energy in longer wavelengths and glows a reddish color. Eventually, no light is given off, but if you place your hand near the metal, you will detect the still-longer infrared radiation as heat. The Sun radiates maximum energy at 0.5 micrometer, which is in the visible range. The maximum radiation for Earth occurs at a wavelength of 10 micrometers, well within the infrared (heat) range. Because the maximum Earth radiation is roughly 20 times longer than the maximum solar radiation, Earth radiation is often called *long-wave radiation*, and solar radiation is called *short-wave radiation.*
- *Objects that are good absorbers of radiation are good emitters as well.* Earth's surface and the Sun are nearly perfect radiators because they absorb and radiate with nearly 100 percent efficiency for their respective temperatures. On the other hand, *gases are selective absorbers and radiators.* Thus, the atmosphere, which is nearly transparent to (does not absorb) certain wavelengths of radiation, is nearly opaque (a good absorber) to others. Our experience tells us that the atmosphere is transparent to visible light; hence, it readily reaches Earth's surface. This is not the case for the longer-wavelength radiation emitted by Earth.

16.5 CONCEPT CHECKS

1. Distinguish between heat and temperature.
2. Describe the three basic mechanisms of heat transfer. Which mechanism is *least* important as a means of heat transfer in the atmosphere?
3. In what part of the electromagnetic spectrum does the Sun radiate maximum energy? How does this compare to Earth?
4. Describe the relationship between the temperature of a radiating body and the wavelengths it emits.

16.6 HEATING THE ATMOSPHERE

Sketch and label a diagram that shows the paths taken by incoming solar radiation. Summarize the greenhouse effect.

The goal of this section is to describe how energy from the Sun heats Earth's surface and atmosphere. It is important to know the paths taken by incoming solar radiation and the factors that cause the amount of solar radiation taking each path to vary.

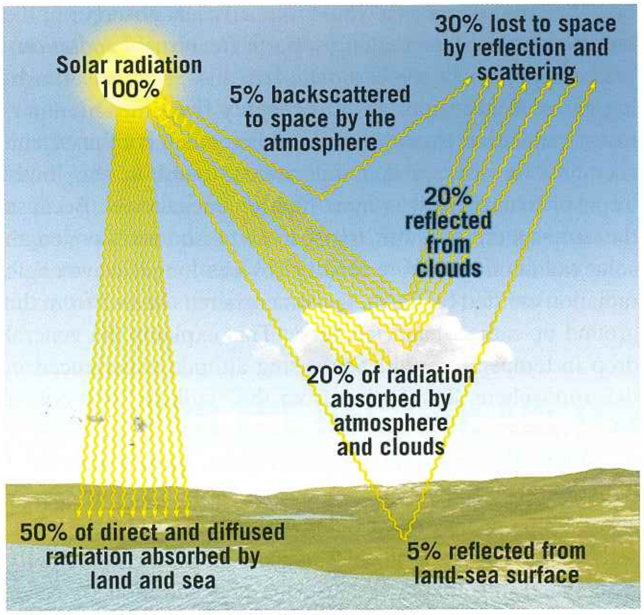
What Happens to Incoming Solar Radiation?

When radiation strikes an object, three different results usually occur. First, some of the energy is *absorbed* by the object. Recall that when radiant energy is absorbed, it is converted to heat, which causes an increase in temperature. Second, substances such as water and air are transparent to certain wavelengths of radiation. Such materials simply *transmit* this energy. Radiation that is transmitted does not contribute energy to the object. Third, some radiation may "bounce off" the object without being absorbed or transmitted. *Reflection* and *scattering* are responsible for redirecting incoming solar radiation. In summary, *radiation may be absorbed, transmitted, or redirected (reflected or scattered).*

FIGURE 16.21 shows the fate of incoming solar radiation averaged for the entire globe. Notice that the atmosphere is quite transparent to incoming solar radiation. On average, about 50 percent of the solar energy that reaches the top of the atmosphere is absorbed at Earth's surface. Another 30 percent is reflected back to space by the atmosphere, clouds, and reflective surfaces. The remaining 20 percent is absorbed by clouds and the atmosphere's gases. What determines whether solar radiation will be transmitted to the surface, scattered, reflected outward, or absorbed by the atmosphere? As you will see, it depends greatly on the wavelength of the energy being transmitted, as well as on the nature of the intervening material.

Reflection and Scattering

Reflection is the process whereby light bounces back from an object at the same angle at which it encounters a surface



SmartFigure 16.21 Paths Taken by Solar Radiation This diagram shows the average distribution of incoming solar radiation, by percentage. More solar radiation is absorbed by Earth's surface than by the atmosphere.

and with the same intensity (**FIGURE 16.22A**). By contrast, **scattering** produces a larger number of weaker rays that travel in different directions. Although scattering disperses light both forward and backward (*backscattering*), more energy is dispersed in the forward direction (**FIGURE 16.22B**).

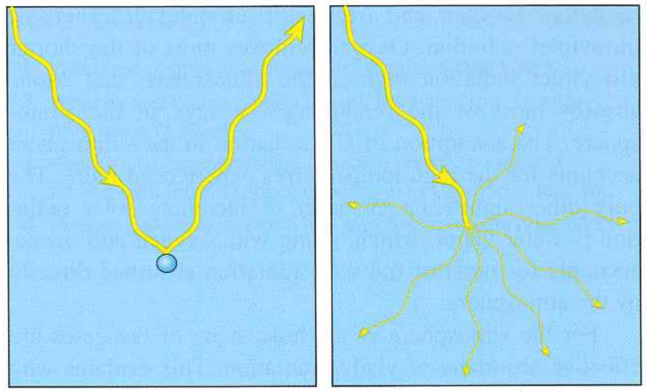
Reflection and Earth's Albedo

Energy is returned to space from Earth in two ways: reflection and emission of radiant energy. The portion of solar energy that is reflected back to space leaves in the same short wavelengths in which it came to Earth. About 30 percent of the solar energy that reaches the outer atmosphere is reflected back to space. Included in this figure is the amount sent skyward by backscattering. This energy is lost to Earth and does not play a role in heating the atmosphere.

The fraction of the total radiation that is reflected by a surface is called its **albedo**. Thus, the albedo for Earth as a whole (the *planetary albedo*) is 30 percent. However, the albedo from place to place as well as from time to time in the same locale varies considerably, depending on the amount of cloud cover and particulate matter in the air, as well as on the angle of the Sun's rays and the nature of the surface. A lower Sun angle means that more atmosphere must be penetrated, thus making the "obstacle course" longer and the loss of solar radiation greater (see Figure 16.14). **FIGURE 16.23** shows the albedos for various surfaces. Note that the angle at which the Sun's rays strike a water surface greatly affects the albedo of that surface.

Scattering

Although incoming solar radiation travels in a straight line, small dust particles and gas molecules in the atmosphere scatter some of this energy in all directions. The result, called **diffused light**, explains how light reaches into the area beneath a shade tree and how a room is lit in the absence of direct sunlight. Further, scattering accounts for the brightness and even the blue color of the daytime sky. In contrast, bodies such as the Moon and Mercury, which are without atmospheres, have dark skies and "pitch-black" shadows, even during daylight hours. Overall, about half of the solar radiation that is absorbed at Earth's surface arrives as diffused (scattered) light.



A. Reflected light bounces back from a surface at the same angle at which it strikes that surface and with the same intensity.

B. When a beam of light is scattered, it results in a larger number of weaker rays, traveling in all directions. Usually more energy is scattered in the forward direction than is backscattered.

FIGURE 16.22 Reflection and Scattering

Absorption

As stated earlier, gases are **selective absorbers**, meaning that they absorb strongly in some wavelengths, moderately in others, and only slightly in still others. When a gas molecule absorbs radiation, the energy is transformed into internal molecular motion, which is detectable as a rise in temperature.

Nitrogen, the most abundant constituent in the atmosphere, is a poor absorber of all types of incoming solar

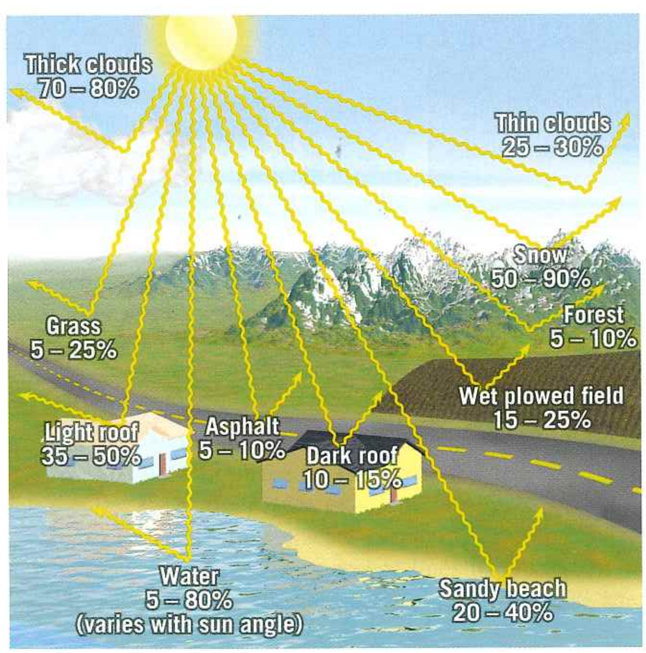


FIGURE 16.23 Albedo (Reflectivity) of Various Surfaces In general, ligh colored surfaces tend to reflect more sunlight than dark-colored surfaces and thus have higher albedos.

radiation. Oxygen and ozone are efficient absorbers of ultraviolet radiation. Oxygen removes most of the shorter ultraviolet radiation high in the atmosphere, and ozone absorbs most of the remaining UV rays in the stratosphere. The absorption of UV radiation in the stratosphere accounts for the high temperatures experienced there. The only other significant absorber of incoming solar radiation is water vapor, which, along with oxygen and ozone, accounts for most of the solar radiation absorbed directly by the atmosphere.

For the atmosphere as a whole, none of the gases are effective absorbers of visible radiation. This explains why most visible radiation reaches Earth's surface and why we say that the atmosphere is *transparent* to incoming solar radiation. Thus, the atmosphere does not acquire the bulk of its energy directly from the Sun. Rather, it is heated chiefly by energy that is first absorbed by Earth's surface and then reradiated to the sky.

SmartFigure 16.24
The Greenhouse Effect
Earth's greenhouse effect is compared with two of our close solar system neighbors.

Heating the Atmosphere: The Greenhouse Effect

Approximately 50 percent of the solar energy that strikes the top of the atmosphere reaches Earth's surface and is absorbed. 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.

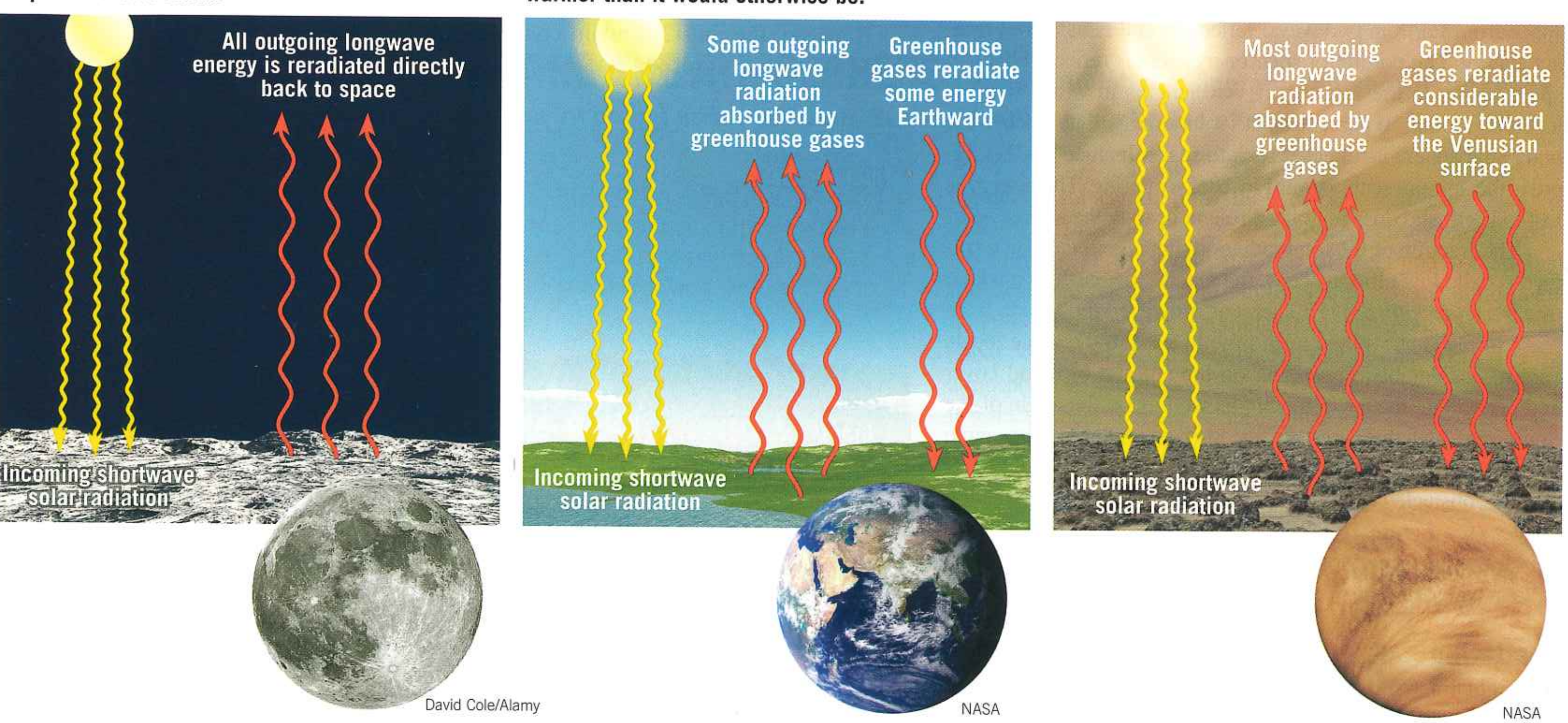
The atmosphere as a whole is an efficient absorber of the longer wavelengths emitted by Earth (*terrestrial radiation*). Water vapor and carbon dioxide are the principal absorbing gases. Water vapor absorbs roughly five times more terrestrial radiation than do all the other gases combined and accounts for the warm temperatures found in the lower troposphere, where it is most highly concentrated. Because the atmosphere is quite transparent to shorter-wavelength solar radiation and more readily absorbs longer-wavelength radiation emitted by Earth, the atmosphere is heated from the ground up rather than vice versa. This explains the general drop in temperature with increasing altitude experienced in the troposphere. The farther from the "radiator," the colder it becomes.

When the gases in the atmosphere absorb terrestrial radiation, they warm; but they eventually radiate this energy away. Some energy travels skyward, where it may be reabsorbed by other gas molecules, a possibility that is less likely with increasing height because the concentration of water vapor decreases with altitude. The remainder travels Earthward and is again absorbed by Earth. For this reason, Earth's surface is continually being supplied with heat from the atmosphere as well as from the Sun. Without these absorptive gases in our atmosphere, Earth would not be a suitable habitat for humans and numerous other life-forms. This very important phenomenon has been termed the **greenhouse effect** because it was once thought that greenhouses were heated in a similar manner (**FIGURE 16.24**).

Airless bodies like the Moon All incoming solar radiation reaches the surface. Some is reflected back to space. The rest is absorbed by the surface and radiated directly back to space. As a result the lunar surface has a much lower average surface temperature than Earth.

Bodies with modest amounts of greenhouse gases like Earth The atmosphere absorbs some of the longwave radiation emitted by the surface. A portion of this energy is radiated back to the surface and is responsible for keeping Earth's surface 33°C (59°F) warmer than it would otherwise be.

Bodies with abundant greenhouse gases like Venus Venus experiences extraordinary greenhouse warming, which is estimated to raise its surface temperature by 523°C (941°F).



The gases of our atmosphere, especially water vapor and carbon dioxide, act very much like the glass in the greenhouse. They allow shorter-wavelength solar radiation to enter, where it is absorbed by the objects inside. These objects in turn radiate energy, but at longer wavelengths, to which glass is nearly opaque. The heat therefore is "trapped" in the greenhouse. However, a more important factor in keeping a greenhouse warm is the fact that the greenhouse itself prevents mixing of air inside with cooler air outside. Nevertheless, the term *greenhouse effect* is still used.

16.6 CONCEPT CHECKS

1. What three paths does incoming solar radiation take?
2. What factors cause albedo to vary from time to time and from place to place?
3. Explain why the atmosphere is heated chiefly by radiation emitted from Earth's surface rather than by direct solar radiation.
4. Prepare a sketch with labels that explains the greenhouse effect.

16.7 FOR THE RECORD: AIR TEMPERATURE DATA

Calculate five commonly used types of temperature data and interpret a map that depicts temperature data using isotherms.

People probably notice changes in air temperature more often than they notice changes in any other element of weather. At a weather station, the temperature is monitored on a regular basis from instruments mounted in an instrument shelter (**FIGURE 16.25**). The shelter protects the instruments from direct sunlight and allows a free flow of air.

The daily maximum and minimum temperatures are the bases for much of the basic temperature data compiled by meteorologists:

- By adding the maximum and minimum temperatures and then dividing by two, the **daily mean temperature** is calculated.
- The **daily range** of temperature is computed by finding the difference between the maximum and minimum temperatures for a given day.
- The **monthly mean** is calculated by adding together the daily means for each day of the month and dividing by the number of days in the month.
- The **annual mean** is an average of the 12 monthly means.
- The **annual temperature range** is computed by finding the difference between the highest and lowest monthly means.

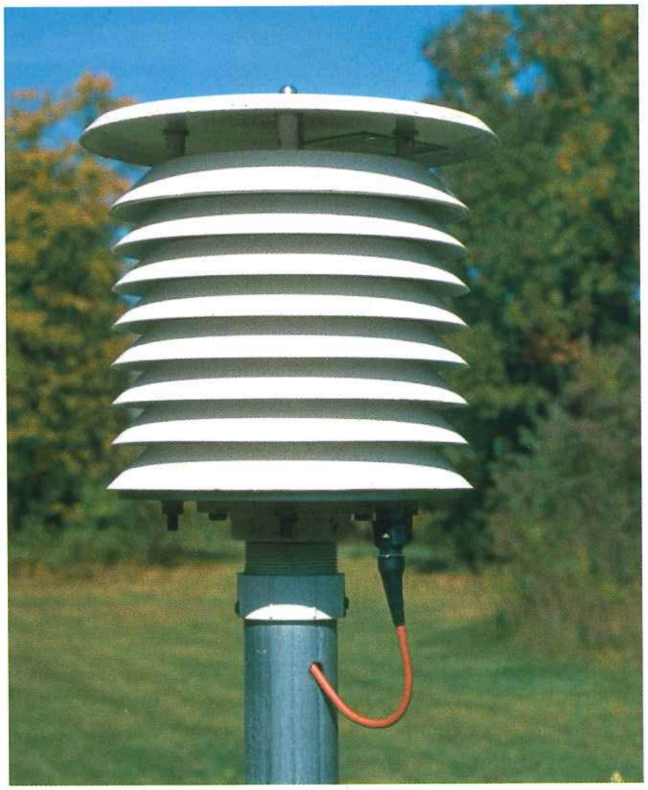


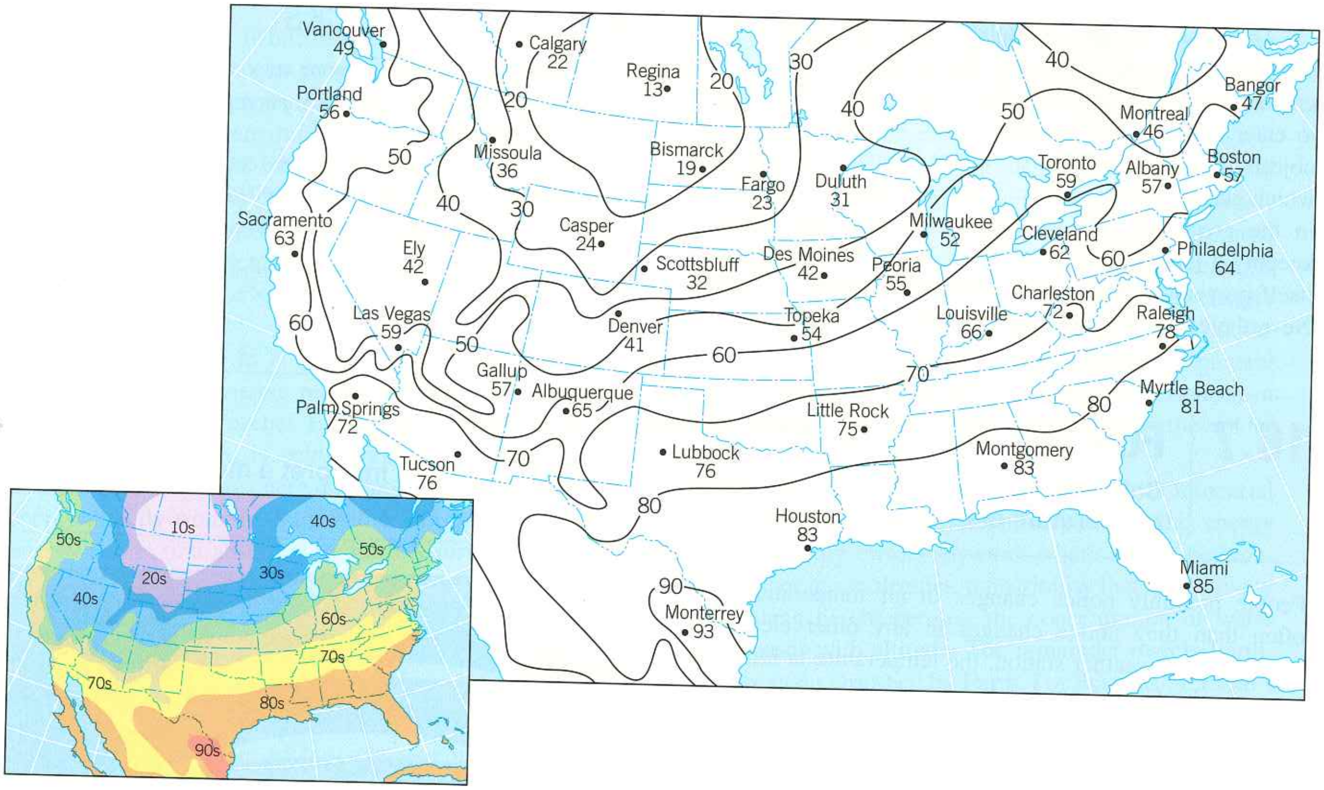
FIGURE 16.25 Measur Temperature This moder shelter contains an electric thermometer called a *thermistor.* A shelter protec instruments from direct sunlight and allows for the free flow of air. (Photo by Bob Christopherson)

Mean temperatures are particularly useful for making comparisons, whether on a daily, monthly, or annual basis. It is quite common to hear a weather reporter state, "Last month was the hottest July on record," or "Today, Chicago was 10 degrees warmer than Miami." Temperature ranges are also useful statistics because they give an indication of extremes.

To examine the distribution of air temperatures over large areas, isotherms are commonly used. An **isotherm** is a line that connects points on a map that have the same temperature (*iso* = equal, *therm* = temperature). Therefore, all points through which an isotherm passes have identical temperatures for the time period indicated. Generally, isotherms representing 5° or 10° temperature differences are used, but any interval may be chosen. **FIGURE 16.26** illustrates how isotherms are drawn on a map. Notice that most isotherms do not pass directly through the observing stations because the station readings may not coincide with the values chosen for the isotherms. Only an occasional station temperature will be exactly the same as the value of the isotherm, so it is usually necessary to draw the lines by estimating the proper position between stations.

Maps with isotherms are valuable tools because they clearly make temperature distribution visible at a glance. Areas of low and high temperatures are easy to pick out. In addition, the amount of temperature change per unit of distance, called the **temperature gradient**, is easy to visualize. Closely spaced isotherms indicate a rapid rate of temperature change, whereas more widely spaced lines indicate a more gradual rate of change. You can see this in Figure 16.26. The

SmartFigure 16.26
sotherms Map showing high emperatures for a spring day. sotherms are lines that connect points of equal temperature. The emperatures on this map are n degrees Fahrenheit. Showing emperature distribution in this vay makes patterns easier to ee. Notice that most isotherms o not pass directly through the bserving stations. It is usually ecessary to draw isotherms by stimating their proper position etween stations. On television nd in many newspapers, emperature maps are in color. ather than labeling isotherms, e area *between* isotherms is beled. For example, the zone etween the 0° and 70° otherms is beled "60s."



isotherms are closer in Colorado and Utah (steeper temperature gradient), whereas the isotherms are spread farther in Texas (gentler temperature gradient). Without isotherms, a map would be covered with numbers representing temperatures at dozens or hundreds of places, which would make patterns difficult to see.

16.7 CONCEPT CHECKS

1. How are the following temperature data calculated: daily mean, daily range, monthly mean, annual mean, and annual range?
2. What are isotherms, and what is their purpose?

16.8 WHY TEMPERATURES VARY: THE CONTROLS OF TEMPERATURE

Discuss the principal controls of temperature and use examples to describe their effects.

A **temperature control** is any factor that causes temperature to vary from place to place and from time to time. Earlier in this chapter we examined the most important cause for temperature variations—differences in the receipt of solar radiation. Because variations in Sun angle and length of daylight depend on latitude, they are responsible for warm temperatures in the tropics and colder temperatures at more poleward locations. Of course, seasonal temperature changes at a given latitude occur as the Sun's vertical rays migrate toward and away from a place during the year.

But latitude is not the only control of temperature; if it were, we would expect all places along the same parallel of latitude to have identical temperatures. This is clearly not the case. For example, Eureka, California, and New York City are both coastal cities at about the same latitude, and both have an annual mean temperature of 11°C (52°F). However, New York City is 9°C (16°F) warmer than Eureka in July and 10°C (18°F) cooler in January. In another example, two cities in Ecuador—Quito and Guayaquil—are relatively close to each other, yet the annual mean temperatures of these two cities differ by 12°C (21°F). To explain these situations and countless others, we must realize that factors other than latitude also exert a strong influence on temperature. In the next sections, we examine these other controls, which include differential heating of land and water, altitude, geographic position, cloud cover and albedo, and ocean currents.[1]

Land and Water

The heating of Earth's surface directly influences the heating of the air above it. Therefore, to understand variations in air temperature, we must understand the variations in heating properties of the different surfaces that Earth presents to the Sun—soil, water, trees, ice, and so on. Different land surfaces absorb varying amounts of incoming solar energy, which in turn cause variations in the temperature of the air above. The greatest contrast, however, is not between

[1]For a discussion of the effects of ocean currents on temperature, see Chapter 15.

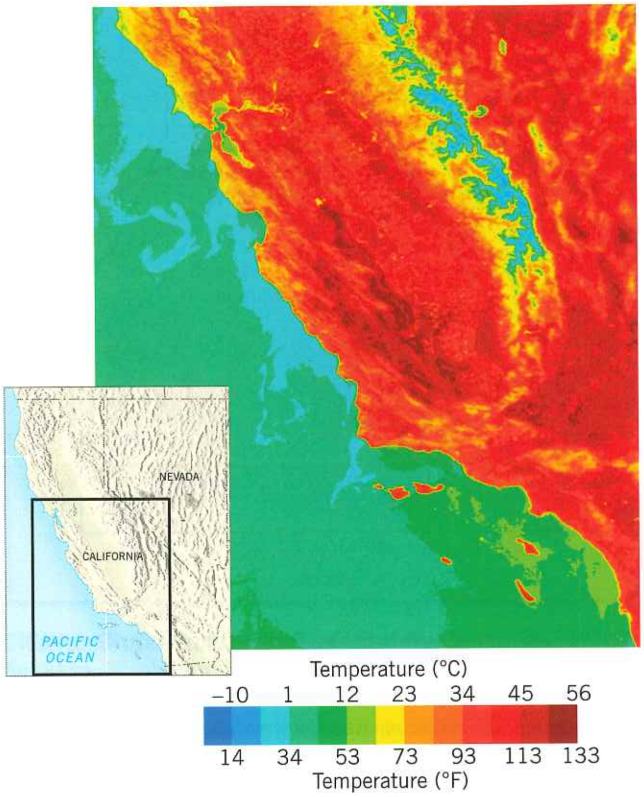


FIGURE 16.27 Differential Heating of Land and Water This satellite image from the afternoon of May 2, 2004, illustrates an important control of air temperature. Water-surface temperatures in the Pacific Ocean are much lower than land-surface temperatures in California and Nevada. The narrow band of cool temperatures in the center of the image is associated with mountains (the Sierra Nevada). The cooler water temperatures immediately offshore are associated with the California Current. (NASA)

different land surfaces but between land and water. **FIGURE 16.27** illustrates this idea nicely. This satellite image shows surface temperatures in portions of Nevada, California, and the adjacent Pacific Ocean on the afternoon of May 2, 2004, during a spring heat wave. Land-surface temperatures are clearly much higher than water-surface temperatures. The image shows the extreme high surface temperatures in southern California and Nevada in dark red.[2] Surface temperatures in the Pacific Ocean are much lower. The peaks of the Sierra Nevada, still capped with snow, form a cool blue line down the eastern side of California.

In side-by-side areas of land and water, such as those shown in Figure 16.27, *land heats more rapidly and to higher temperatures than water, and it cools more rapidly and to lower temperatures than water.* Variations in air temperatures, therefore, are much greater over land than over water.

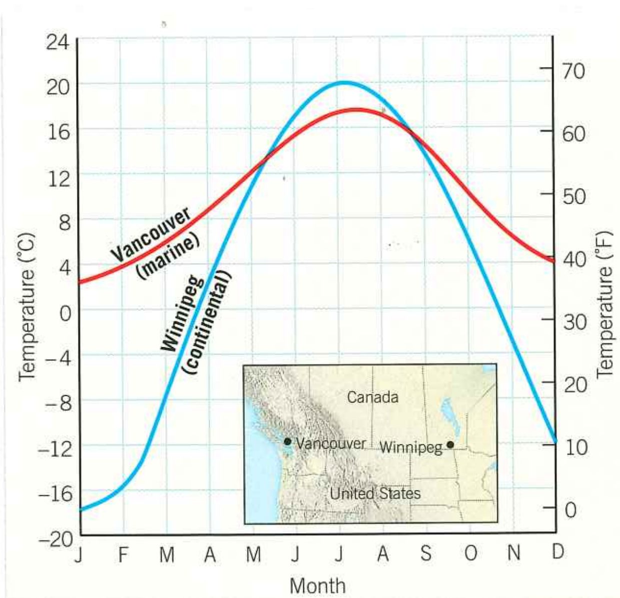
Why do land and water heat and cool differently? Several factors are responsible:

- The **specific heat** (the amount of energy needed to raise the temperature of 1 gram of a substance 1°C) is far greater for water than for land. Thus, water requires a great deal more heat to raise its temperature the same amount than does an equal quantity of land.
- Land surfaces are opaque, so heat is absorbed only at the surface. Water, being more transparent, allows heat to penetrate to a depth of many meters.
- The water that is heated often mixes with water below, thus distributing the heat through an even larger mass.
- Evaporation (a cooling process) from water bodies is greater than that from land surfaces.

All these factors collectively cause water to warm more slowly, store greater quantities of heat, and cool more slowly than land.

Monthly temperature data for two cities will demonstrate the moderating influence of a large water body and the extremes associated with land (**FIGURE 16.28**). Vancouver, British Columbia, is located along the windward Pacific coast, whereas Winnipeg, Manitoba, is in a continental position far from the influence of water. Both cities are at about the same latitude and thus experience similar Sun angles and lengths of daylight. Winnipeg, however, has a mean January temperature that is 20°C lower than Vancouver's. Conversely, Winnipeg's July mean is 2.6°C higher than Vancouver's. Although their latitudes are nearly the same, Winnipeg, which has no water influence, experiences much greater temperature extremes than does Vancouver. The key to Vancouver's moderate year-round climate is the Pacific Ocean.

On a different scale, the moderating influence of water may also be demonstrated when temperature variations in the Northern and Southern Hemispheres are compared. In the Northern Hemisphere, 61 percent is covered by water, and land accounts for the remaining 39 percent. However, in the Southern Hemisphere, 81 percent is covered by water and 19 percent by land. The Southern Hemisphere is correctly called the *water hemisphere* (see Figure 13.1, page 410). **TABLE 16.2** portrays the considerably smaller annual temperature variations in the water-dominated Southern Hemisphere as compared with the Northern Hemisphere.



SmartFigure 16.28 Monthly Mean Temperatures for Vancouver, British Columbia, and Winnipeg, Manitoba Vancouver has a much smaller annual temperature range because of the strong marine influence of the Pacific Ocean. The curve for Winnipeg illustrates the greater extremes associated with an interior location.

[2] Realize that when a land surface is hot, the air above is cooler. For example, while the surface of a sandy beach can be painfully hot, the air temperature above the surface is more comfortable.

TABLE 16.2 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

Altitude

The two cities in Ecuador mentioned earlier—Quito and Guayaquil—demonstrate the influence of altitude on mean temperatures. Although both cities are near the equator and not far apart, the annual mean temperature at Guayaquil is 25°C (77°F), as compared to Quito's mean of 13°C (55°F). The difference is explained largely by the difference in the cities' elevations: Guayaquil is only 12 meters (40 feet) above sea level, whereas Quito is high in the Andes Mountains, at 2800 meters (9200 feet). **FIGURE 16.29** provides another example.

Recall that temperatures drop an average of 6.5°C per kilometer in the troposphere; thus, cooler temperatures are to be expected at greater heights. Yet the magnitude of the difference is not explained completely by the normal lapse rate. If the normal lapse rate is used, we would expect Quito to be about 18°C cooler than Guayaquil, but the difference is only 12°C. The fact that high-altitude places such as Quito are warmer than the value calculated using the normal lapse rate results from the absorption and reradiation of solar energy by the ground surface.

Geographic Position

The geographic setting can greatly influence the temperatures experienced at a specific location. 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.

A leeward coast, on the other hand, will have a more continental temperature pattern because the winds do not carry the ocean's influence onshore. Eureka, California, and New York City, the two cities mentioned earlier, illustrate this aspect of geographic position. The annual temperature range at New York City is 19°C (34°F) greater than Eureka's (**FIGURE 16.30**).

Seattle and Spokane, both in the state of Washington, illustrate a second aspect of geographic position: mountains that act as barriers. Although Spokane is only about 360 kilometers (220 miles) east of Seattle, the towering Cascade Range separates the cities. Consequently, Seattle's temperatures show a marked marine influence, but Spokane's are more typically continental (**FIGURE 16.31**). Spokane is 7°C (13°F) cooler than Seattle in January and 4°C (7°F) warmer than Seattle in July. The annual range at Spokane is 11°C (20°F) greater than at Seattle. The Cascade Range effectively cuts off Spokane from the moderating influence of the Pacific Ocean.

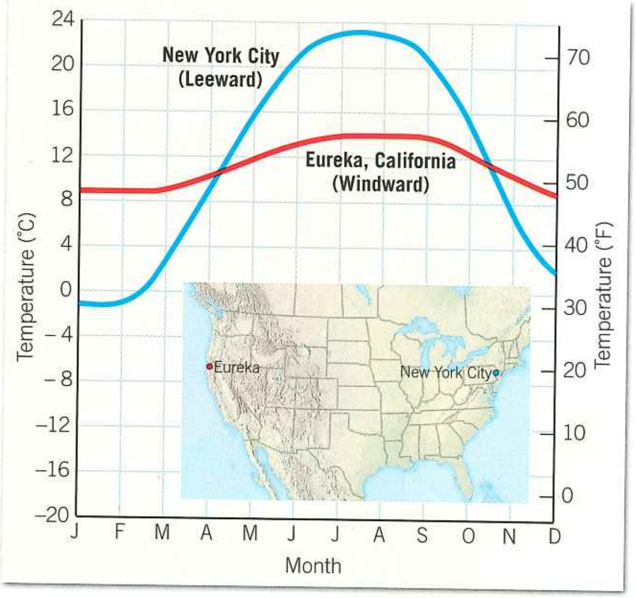
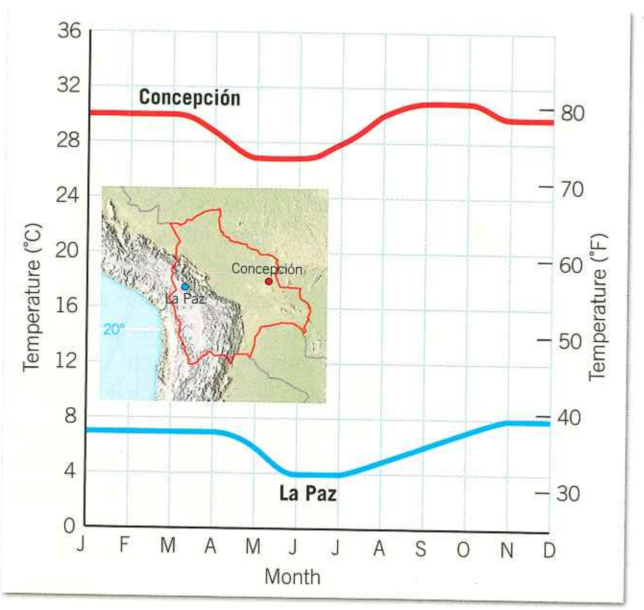


FIGURE 16.30 Monthly Mean Temperatures for Eureka, California, and New York City Both cities are coastal and located at about the same latitude. Because Eureka is strongly influenced by prevailing winds from the ocean and New York City is not, the annual temperature range at Eureka is much smaller.



IGURE 16.29 Monthly ean Temperatures for oncepción and La Paz, olivia Both cities have early the same latitude bout 16° south). However, ecause La Paz is high in e Andes, at 4103 meters 3,461 feet), it experiences uch cooler temperatures an Concepción, which is at elevation of 490 meters 608 feet).

Cloud Cover and Albedo

You may have noticed that clear days are often warmer than cloudy ones and that clear nights are usually cooler than cloudy ones. This demonstrates that cloud cover is another factor that influences temperature in the lower atmosphere. Studies using satellite images show that at

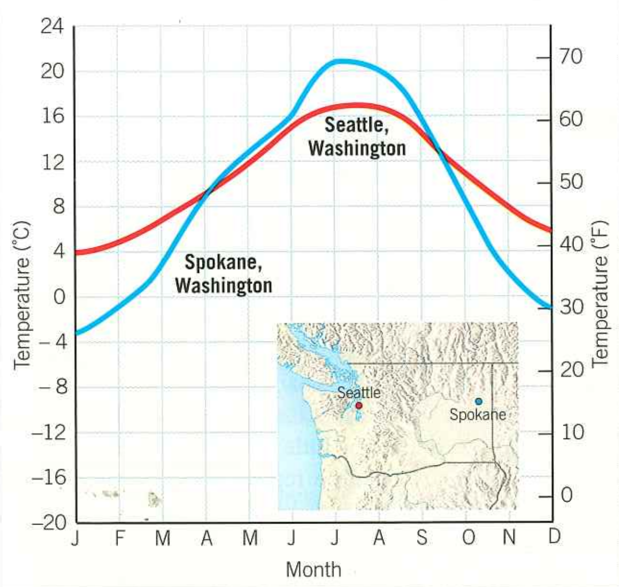
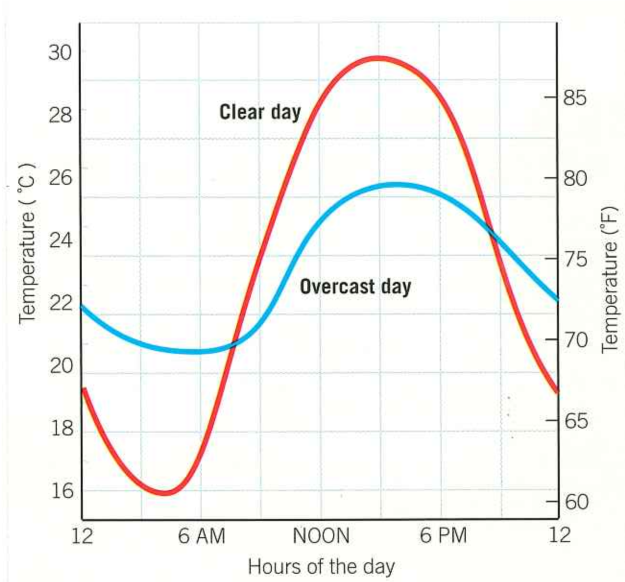


FIGURE 16.31 Monthly Mean Temperatures for Seattle and Spokane, Washington Because the Cascade Mountains cut off Spokane from the moderating influence of the Pacific Ocean, Spokane's annual temperature range is greater than Seattle's.



SmartFigure 16.32 The Daily Cycle of Temperature at Peoria, Illinois, for Two July Days Clouds reduce the daily temperature range. During daylight hours, clouds reflec[t] solar radiation back to spac[e]. Therefore, the maximum temperature is lower than if the sky were clear. At night, the minimum temperature w[ill] not fall as low because clouds retard the loss of heat.

any particular time, about half of our planet is covered by clouds. Cloud cover is important because many clouds have a high albedo; therefore, clouds reflect a significant portion of the sunlight that strikes them back into space (see Figure 16.23). Cloud cover reduces the amount of incoming solar radiation, and daytime temperatures will be lower than if the clouds were not present and the sky were clear.

At night, clouds have the opposite effect as during daylight: They act as a blanket by absorbing radiation emitted by Earth's surface and reradiating a portion of it back to the surface. Consequently, some of the heat that otherwise would have been lost remains near the ground. Thus, 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 (**FIGURE 16.32**).

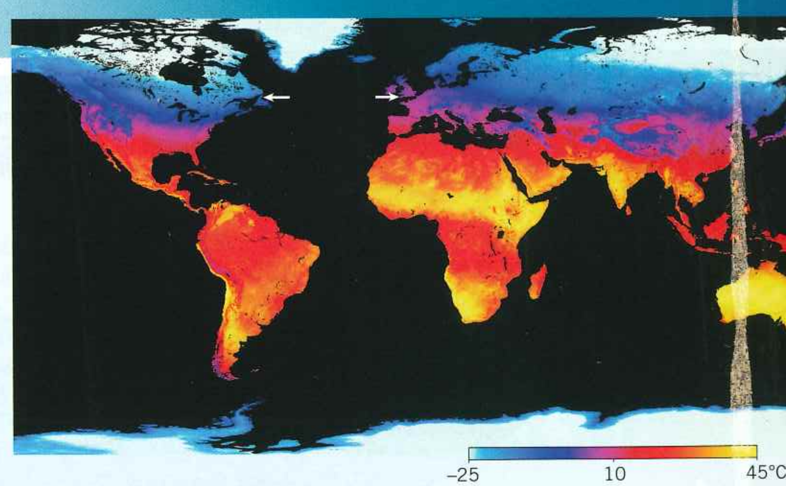
Clouds are not the only phenomenon that increase albedo and thereby reduces air temperatures. We also recognize that snow- and ice-covered surfaces have high albedos. This is one reason why mountain glaciers do not melt away in the summer and why snow may still be present on a mild spring day. In addition, during the winter, when snow covers the ground, daytime maximums on a sunny day are less than they otherwise would be because energy that the land would have absorbed and used to heat the air is reflected and lost.

16.8 CONCEPT CHECKS

1. List the factors that cause land and water to heat and cool differently.
2. Quito, Ecuador, is located on the equator and is *not* a coastal city. It has an average annual temperature of only 13°C (55°F). What is the likely cause for this low average temperature?
3. In what ways can geographic position be considered a control of temperature?
4. How does cloud cover influence the maximum temperature on an overcast day? How is the nighttime minimum influenced by clouds?

EYE ON EARTH

For more than a decade, scientists have used the Moderate Resolution Imaging Spectroradiometer (MODIS, for short) aboard NASA's *Aqua* and *Terra* satellites to gather surface temperature data from around the globe. This image shows average land-surface temperatures for the month of February over a 10-year span (2001–2010). (NASA)



QUESTION 1 *What are the approximate temperatures for southern Great Britain and northern Newfoundland (white arrows)?*

QUESTION 2 *Both southern Great Britain and northern Newfoundland are coastal areas at the same latitude, yet average February temperatures are quite different. Suggest a reason for this disparity.*

16.9 WORLD DISTRIBUTION OF TEMPERATURE

Interpret the patterns depicted on world maps of January and July temperatures.

Take a moment to study the two world isothermal maps in **FIGURES 16.33** and **16.34**. From hot colors near the equator to cool colors toward the poles, these maps portray sea-level temperatures in the seasonally extreme months of January and July. Temperature distribution is shown by using isotherms. On these maps you can study global temperature patterns and the effects of the controlling factors of temperature, especially latitude, the distribution of land and water, and ocean currents. Like most other isothermal maps of large regions, all temperatures on these world maps have been reduced to sea level to eliminate the complications caused by differences in altitude.

On both maps, the isotherms generally trend east and west and show a decrease in temperatures poleward from the tropics. They illustrate one of the most fundamental aspects of world temperature distribution: that the effectiveness of incoming solar radiation in heating Earth's surface and the atmosphere above it is largely a function of latitude.

Moreover, there is a latitudinal shifting of temperatures caused by the seasonal migration of the Sun's vertical rays. To see this, compare the color bands by latitude on the two maps. On the January map, the "hot spots" of 30°C are *south* of the equator, but in July they have shifted *north* of the equator.

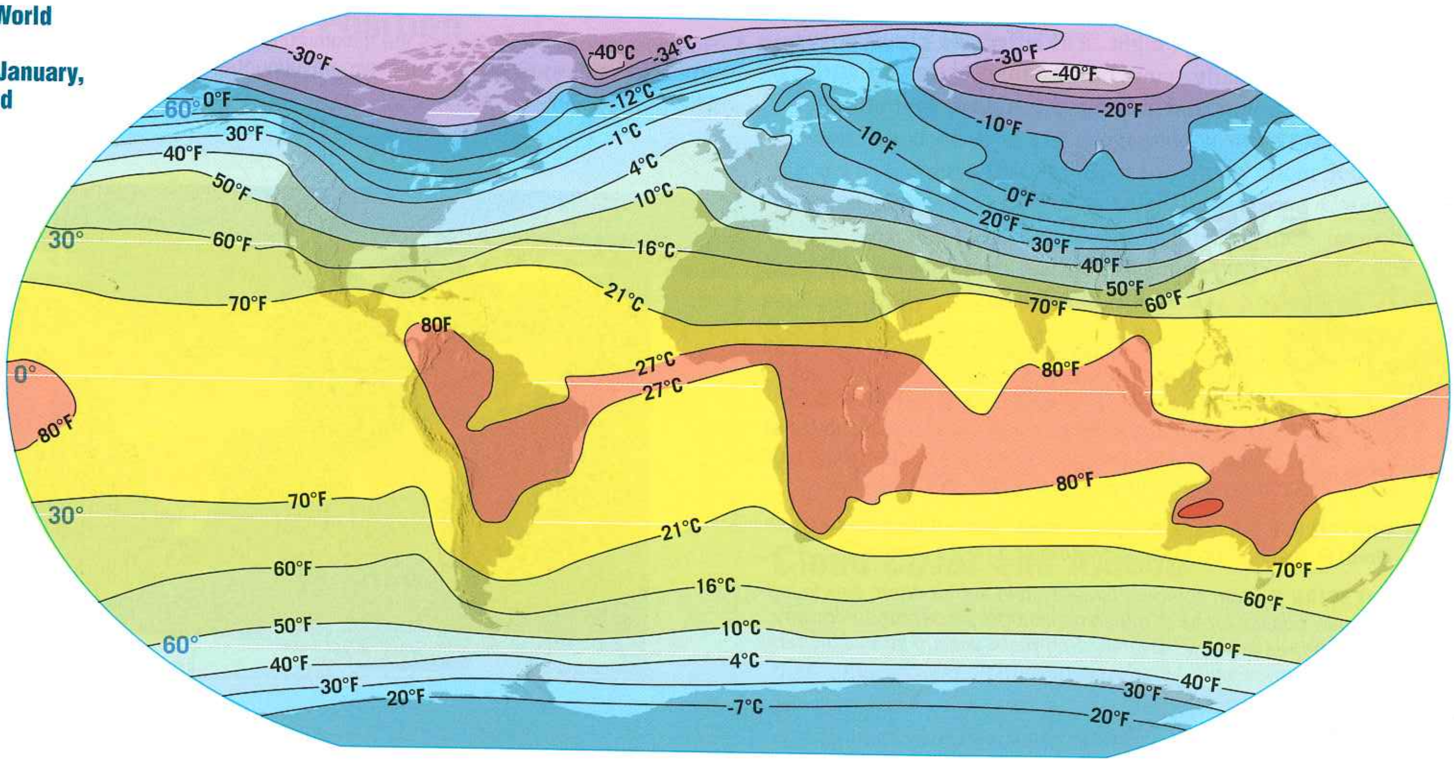
If latitude were the only control of temperature distribution, our analysis could end here, but that is not the case. The added effect of the differential heating of land and water is also reflected on the January and July temperature maps. The warmest and coldest temperatures are found over land; note the coldest area, a purple oval in Siberia, and the hottest areas, the deep orange ovals, all over land. Because temperatures do not fluctuate as much over water as over land, the north–south migration of isotherms is greater over the continents than over the oceans.

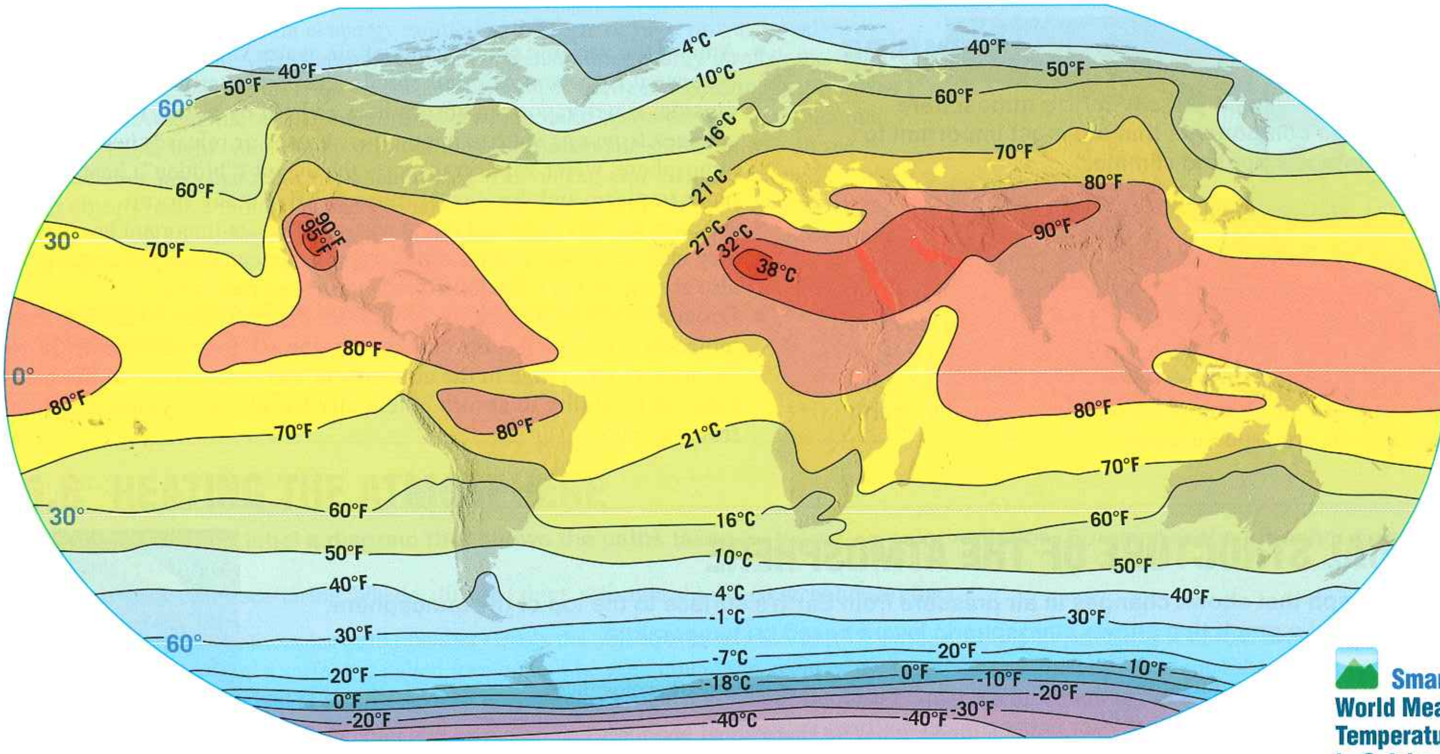
In addition, it is clear that the isotherms in the Southern Hemisphere, where there is little land and where the oceans predominate, are much more regular than in the Northern Hemisphere, where they bend sharply northward in July and southward in January over the continents.

Isotherms also show the presence of ocean currents. Warm currents cause isotherms to be deflected toward the poles, whereas cold currents cause an equatorward bending. The horizontal transport of water poleward warms the overlying air and results in air temperatures that are higher than would otherwise be expected for the latitude. Conversely, currents moving toward the equator produce cooler-than-expected air temperatures.

Because Figures 16.33 and 16.34 show the seasonal extremes of temperature, they can be used to evaluate variations in the annual range of temperature from place to place. A comparison of the two maps shows that a station near the equator has a very small annual range because it experiences little variation in the length of daylight, and it always has a relatively high Sun angle. A station in the middle latitudes, however, experiences wide variations in Sun angle and length of daylight and hence large variations in temperature. Therefore, we can state that the

FIGURE 16.33 World Mean Sea-Level Temperatures in January, in Celsius (°C) and Fahrenheit (°F)





SmartFigure 16.3 World Mean Sea-Level Temperatures in July, in Celsius (°C) and Fahrenheit (°F)

annual temperature range increases with an increase in latitude.

Moreover, land and water also affect seasonal temperature variations, especially outside the tropics. A continental location must endure hotter summers and colder winters than a coastal location. Consequently, outside the tropics, the annual temperature range will increase with an increase in continentality.

16.9 CONCEPT CHECKS

1 Why do isotherms generally trend east–west?
2 Why do isotherms shift north and south from season to season?
3 Where do isotherms shift most, over land or water? Explain.
4 Which area on Earth experiences the highest annual temperature range?

16 CONCEPTS IN REVIEW

The Atmosphere: Composition, Structure, and Temperature

16.1 FOCUS ON THE ATMOSPHERE

Distinguish between weather and climate and name the basic elements of weather and climate.

KEY TERMS: weather, climate, elements (of weather and climate)

- Weather is the state of the atmosphere at a particular place for a short period of time. Climate, on the other hand, is a generalization of the weather conditions of a place over a long period of time.
- The most important elements—quantities or properties that are measured regularly—of weather and climate are (1) air temperature, (2) humidity, (3) type and amount of cloudiness, (4) type and amount of precipitation, (5) air pressure, and (6) the speed and direction of the wind.

Q This is a scene on a summer day in Antarctica, showing a joint British–American research team. Write two brief statements about the locale in this image—one that relates to weather and one that relates to climate.

David Vaughan/Science Source

16.2 COMPOSITION OF THE ATMOSPHERE

List the major gases composing Earth's atmosphere and identify the components that are most important to understanding weather and climate.

KEY TERMS: air, aerosols, ozone

- Air is a mixture of many discrete gases, and its composition varies from time to time and from place to place. If water vapor, dust, and other variable components of the atmosphere are removed, clean, dry air is composed almost entirely of nitrogen (N_2) and oxygen (O_2). Carbon dioxide (CO_2), although present only in minute amounts, is important because it has the ability to absorb heat radiated by Earth and thus helps keep the atmosphere warm.
- Among the variable components of air, water vapor is important because it is the source of all clouds and precipitation. Like carbon dioxide, water vapor can absorb heat emitted by Earth. When water changes from one state to another, it absorbs or releases heat. In the atmosphere, water vapor transports this latent ("hidden") heat from place to place, and this energy helps to drive many storms.
- Aerosols are tiny solid and liquid particles that are important because they may act as surfaces on which water vapor can condense and are also absorbers and reflectors of incoming solar radiation.
- Ozone, a form of oxygen that combines three oxygen atoms into each molecule (O_3), is a gas concentrated in the 10- to 50-kilometer (6- to 31-mile) height range in the atmosphere and is important to life because of its ability to absorb potentially harmful ultraviolet radiation from the Sun.

16.3 VERTICAL STRUCTURE OF THE ATMOSPHERE

Interpret a graph that shows changes in air pressure from Earth's surface to the top of the atmosphere. Sketch and label a graph that shows atmospheric layers based on temperature.

KEY TERMS: troposphere, environmental lapse rate, radiosonde, stratosphere, mesosphere, thermosphere

- Because the atmosphere gradually thins with increasing altitude, it has no sharp upper boundary but simply blends into outer space.
- Based on temperature, the atmosphere is divided vertically into four layers. The *troposphere* is the lowermost layer. In the troposphere, temperature usually decreases with increasing altitude. This *environmental lapse rate* is variable but averages about 6.5°C per kilometer (3.5°F per 1000 feet). Essentially, all important weather phenomena occur in the troposphere.
- Beyond the troposphere is the *stratosphere*, which exhibits warming because of absorption of UV radiation by ozone. In the *mesosphere*, temperatures again decrease. Upward from the mesosphere is the *thermosphere*, a layer with only a tiny fraction of the atmosphere's mass and no well-defined upper limit.

Q When the weather balloon in this photo was launched, the surface temperature was 17°C. The balloon is now at an altitude of 1 kilometer. What term is applied to the instrument package being carried aloft by the balloon? In what layer of the atmosphere is the balloon? If average conditions prevail, what is the air temperature at this altitude? How did you figure this out?

David R. Frazier/Science Source

16.4 EARTH—SUN RELATIONSHIPS

Explain what causes the Sun angle and length of daylight to change during the year and describe how these changes produce the seasons.

EY TERMS: rotation, circle of illumination, revolution, inclination of the xis, Tropic of Cancer, summer solstice, Tropic of Capricorn, winter solstice, utumnal (fall) equinox, spring equinox

- The two principal motions of Earth are (1) rotation, the spinning about its axis that produces the daily cycle of daylight and darkness, and (2) revolution, the movement in its orbit around the Sun.
- The seasons are caused by changes in the angle at which the Sun's rays strike the surface and the changes in the length of daylight at each latitude. These seasonal changes are the result of the tilt of Earth's axis as it revolves around the Sun.

Q Assume that the date is December 22. At what latitude are the Sun's vertical rays striking? Is this date an equinox or a solstice?

6.5 ENERGY, HEAT, AND TEMPERATURE

Distinguish between heat and temperature. List and describe the three mechanisms of heat transfer.

EY TERMS: heat, temperature, conduction, convection, radiation, electromagnetic radiation, visible light, infrared, ultraviolet (UV)

- Heat refers to the quantity of energy present in a material, whereas temperature refers to intensity, or the degree of "hotness."
- The three mechanisms of heat transfer are (1) conduction, the transfer of heat through matter by molecular activity; (2) convection, the transfer of heat by the movement of a mass or substance from one place to another; and (3) radiation, the transfer of heat by electromagnetic waves.

- Electromagnetic radiation is energy emitted in the form of rays, or waves, called electromagnetic waves. All radiation is capable of transmitting energy through the vacuum of space. One of the most important differences between electromagnetic waves is their wavelengths, which range from very long radio waves to very short gamma rays. Visible light is the only portion of the electromagnetic spectrum we can see.
- Some basic laws that relate to radiation are (1) all objects emit radiant energy; (2) hotter objects radiate more total energy than do colder objects; (3) the hotter the radiating body, the shorter the wavelengths of maximum radiation; and (4) objects that are good absorbers of radiation are good emitters as well.

Q Describe how each of the three basic mechanisms of heat transfer are illustrated in this image.

Johner Images RF/AGE Fotostock

16.6 HEATING THE ATMOSPHERE

Sketch and label a diagram that shows the paths taken by incoming solar radiation. Summarize the greenhouse effect.

KEY TERMS: reflection, scattering, albedo, diffused light, selective absorbers, greenhouse effect

- About 50 percent of the solar radiation that strikes the atmosphere reaches Earth's surface. About 30 percent is reflected back to space. The fraction of radiation reflected by a surface is called its albedo. The remaining 20 percent of the energy is absorbed by clouds and the atmosphere's gases.
- Radiant energy absorbed at Earth's surface is eventually radiated skyward. Because Earth has a much lower surface temperature than the Sun, its radiation is in the form of long-wave infrared radiation. Because atmospheric gases, primarily water vapor and carbon dioxide, are more efficient absorbers of long-wave radiation, the atmosphere is heated from the ground up.
- The selective absorption of Earth radiation by water vapor and carbon dioxide that results in Earth's average temperature being warmer than it would be otherwise is referred to as the greenhouse effect.

16.7 FOR THE RECORD: AIR TEMPERATURE DATA

Calculate five commonly used types of temperature data and interpret a map that depicts temperature data using isotherms.

KEY TERMS: daily mean temperature, daily range, monthly mean, annual mean, annual temperature range, isotherm, temperature gradient

- Daily mean temperature is an average of the daily maximum and daily minimum temperatures, whereas the daily range is the difference between the daily maximum and daily minimum temperatures. The monthly mean is determined by averaging the daily means for a particular month. The annual mean is an average of the 12 monthly means, whereas the annual temperature range is the difference between the highest and lowest monthly means.
- Temperature distribution is shown on a map by using isotherms, which are lines of equal temperature. Temperature gradient is the amount of temperature change per unit of distance. Closely spaced isotherms indicate a rapid rate of change.

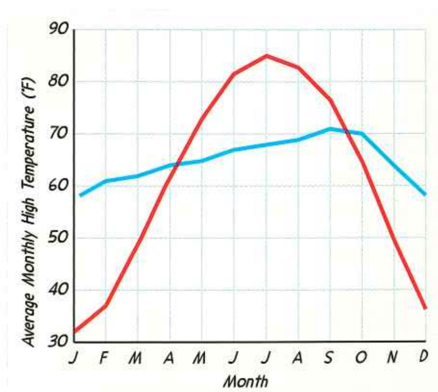
16.8 WHY TEMPERATURES VARY: THE CONTROLS OF TEMPERATURE

Discuss the principal controls of temperature and use examples to describe their effects.

KEY TERMS: temperature control, specific heat, windward coast, leeward coast

- Controls of temperature are factors that cause temperature to vary from place to place and from time to time. Latitude (Earth–Sun relationships) is one example. Ocean currents (discussed in Chapter 10) provide another example.
- Unequal heating of land and water is a temperature control. Because land and water heat and cool differently, land areas experience greater temperature extremes than water-dominated areas.
- Altitude is an easy-to-visualize control: The higher up you go, the colder it gets; therefore, mountains are cooler than adjacent lowlands.
- Geographic position as a temperature control involves factors such as mountains acting as barriers to marine influence and a place being on a windward or a leeward coast.

Q The graph shows monthly high temperatures for Urbana, Illinois, and San Francisco, California. Although the two cities are located at about the same latitude, the temperatures they experience are quite different. Which line on the graph represents Urbana, and which represents San Francisco? How did you figure this out?



16.9 WORLD DISTRIBUTION OF TEMPERATURE

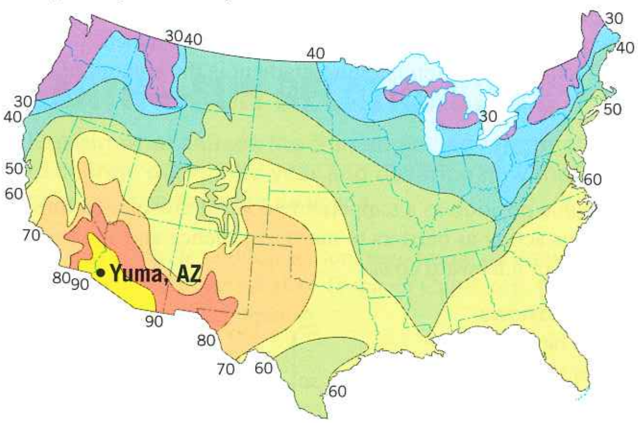
Interpret the patterns depicted on world maps of January and July temperatures.

- On world maps showing January and July mean temperatures, isotherms generally trend east–west and show a decrease in temperature moving poleward from the equator. When the two maps are compared, a latitudinal shifting of temperatures is seen. Bending isotherms reveal the locations of ocean currents.
- Annual temperature range is small near the equator and increases with an increase in latitude. Outside the tropics, annual temperature range also increases as marine influence diminishes.

Q Refer to Figure 16.33. What causes the bend or kink in the isotherms in the North Atlantic?

GIVE IT SOME THOUGHT

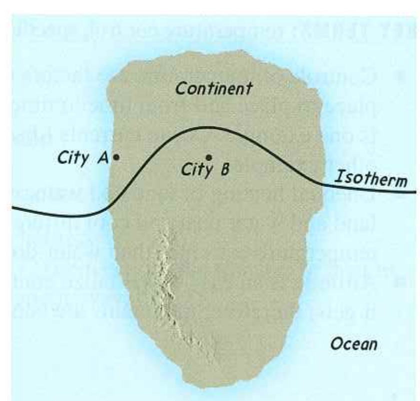
1. Determine which statements refer to weather and which refer to climate. (*Note:* One statement includes aspects of *both* weather and climate.)
   - **a.** The baseball game was rained out today.
   - **b.** January is Omaha's coldest month.
   - **c.** North Africa is a desert.
   - **d.** The high this afternoon was 25°C.
   - **e.** Last evening a tornado ripped through central Oklahoma.
   - **f.** I am moving to southern Arizona because it is warm and sunny.
   - **g.** Thursday's low of −20°C is the coldest temperature ever recorded for that city.
   - **h.** It is partly cloudy.
2. This map shows the mean percentage of possible sunshine received in the month of November across the 48 contiguous United States.
   - **a.** Does this map relate more to climate or to weather?
   - **b.** If you visited Yuma, Arizona, in November, would you *expect* to experience a sunny day or an overcast day?
   - **c.** Might what you actually experience during your visit be different from what you expected? Explain.



3. Refer to the graph in Figure 16.3 to answer the following questions about temperatures in New York City:
   - **a.** What is the approximate average daily high temperature in January? In July?
   - **b.** Approximately what are the highest and lowest temperatures ever recorded?
4. Which of the three mechanisms of heat transfer is clearly illustrated in each of the following situations?
   - **a.** Driving a car with the seat heater turned on
   - **b.** Sitting in an outdoor hot tub
   - **c.** Lying inside a tanning bed
   - **d.** Driving a car with the air conditioning turned on
5. The circumference of Earth at the equator is 24,900 miles. Calculate how fast someone at the equator is rotating in miles per hour. If the rotational speed of Earth were to slow down, how might this impact daytime highs and nighttime lows?
6. Rank the following according to the wavelengths of radiant energy each emits, from the shortest wavelengths to the longest:
   - **a.** A light bulb with a filament glowing at 4000°C
   - **b.** A rock at room temperature
   - **c.** A car engine at 140°C
7. Imagine being at the beach in this photo on a sunny summer afternoon.
   - **a.** Describe the temperatures you would expect if you measured the surface of the beach and at a depth of 12 inches in the sand.
   - **b.** If you stood waist deep in the water and measured the water's surface temperature and its temperature at a depth of 12 inches, how would these measurements compare to those taken on the beach?

Tequilab/Shutterstock

8. On which summer day would you expect the *greatest* temperature range? Which would have the *smallest* range in temperature? Explain your choices.
   - **a.** Cloudy skies during the day and clear skies at night
   - **b.** Clear skies during the day and cloudy skies at night
   - **c.** Clear skies during the day and clear skies at night
   - **d.** Cloudy skies during the day and cloudy skies at night
9. The accompanying sketch map represents a hypothetical continent in the Northern Hemisphere. One isotherm has been placed on the map.
   - **a.** Is the temperature higher at City A or City B?
   - **b.** Is the season winter or summer? How are you able to determine this?
   - **c.** Describe (or sketch) the position of this isotherm 6 months later.



10. This photo shows a snow-covered area in the middle latitudes on a sunny day in late winter. Assume that 1 week after this photo was taken, conditions were essentially identical, except that the snow was gone. Would you expect the air temperatures to be different on the two days? If so, which day would be warmer? Suggest an explanation.

CoolR/Shutterstock

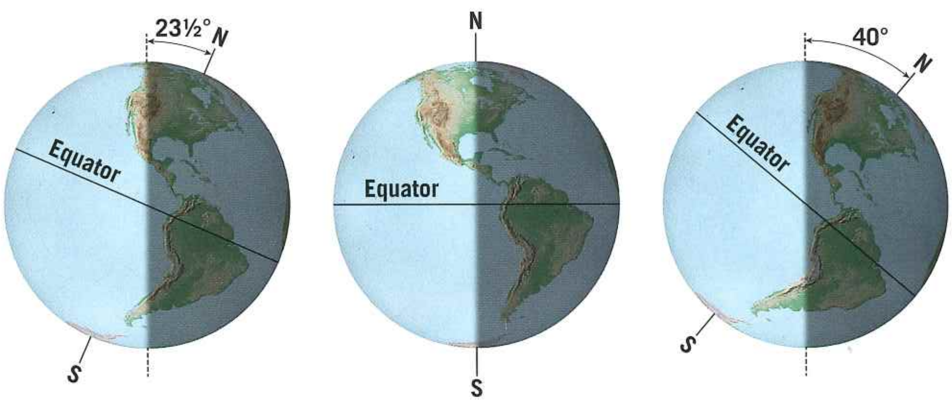
11. The Sun shines continually at the North Pole for 6 months, from the spring equinox until the fall equinox, yet temperatures never get very warm. Explain why this is the case.

12. The data below are mean monthly temperatures in degrees Celsius for an inland location that lacks any significant ocean influence. *Based on annual temperature range*, what is the approximate latitude of this place? Are these temperatures what you would normally expect for this latitude? If not, what control would explain these temperatures?

J	F	M	A	M	J	J	A	S	O	N	D
6.1	6.6	6.6	6.6	6.6	6.1	6.1	6.1	6.1	6.1	6.6	6.6

EXAMINING THE **EARTH SYSTEM**

1. Earth's axis is inclined 23½° to the plane of its orbit. What if the inclination of the axis changed? Answer the following questions that address this possibility:
   - **a.** How would seasons be affected if Earth's axis were perpendicular to the plane of its orbit?
   - **b.** Describe the seasons if Earth's axis were inclined 40°. Where would the Tropics of Cancer and Capricorn be located? How about the Arctic and Antarctic Circles?



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

3. The accompanying photo shows the explosive 1991 eruption of Mt. Pinatubo in the Philippines. How would you expect global temperatures to respond to the ash and debris that this volcano spewed high into the atmosphere? Speculate about how a change in temperature might impact one or more of the spheres in the Earth system.

D. Harlow/USGS

4. Figure 16.21 shows that about 30 percent of the Sun's energy is reflected and scattered back to space. If Earth's albedo were to increase to 50 percent, how would you expect average surface temperatures to change? Explain.

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