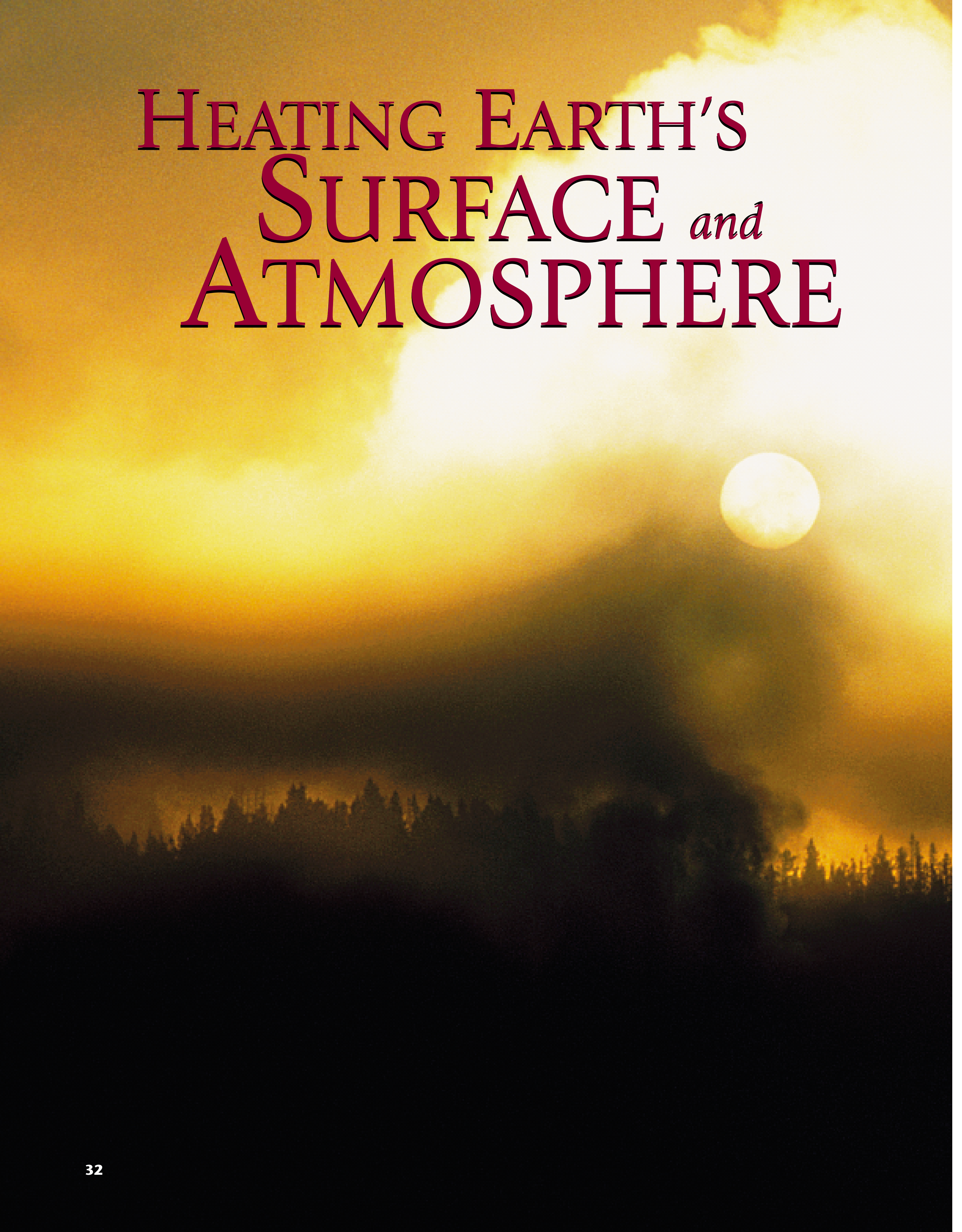
HEATING EARTH'S SURFACE *and* ATMOSPHERE



CHAPTER

2

Solar radiation provides more than 99.9 percent of the energy that heats Earth's surface. *(Photo by Shin Yoshino/Minden Pictures)*

From our everyday experiences, we know that the Sun's rays feel hotter on a clear day than on an overcast day. After taking a barefoot walk on a sunny day, we realize that city pavement becomes much hotter than a grassy boulevard. A picture of a snowcapped mountain reminds us that temperature decreases with altitude. And we know that the fury of winter is always replaced by the newness of spring. You may not know, however, that these occurrences are manifestations of the same phenomenon that causes the blue color of the sky and the red color of a brilliant sunset. All such common occurrences are a result of the interaction of solar radiation with Earth's atmosphere and its land–sea surface (Figure 2–1). That is the essence of this chapter.

Earth–Sun Relationships

GEODe ATMOSPHERE **Heating Earth's Surface and Atmosphere**

▶ Understanding Seasons

Earth intercepts only a minute percentage of the energy given off by the Sun—less than one two-billionth. This may seem an insignificant amount until we realize that it is several hundred thousand times the electrical generating capacity of the United States. Solar radiation, in fact, represents more than 99.9 percent of the energy that heats our planet.

Solar energy is not distributed equally 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 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 we shall 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 that produces the daily cycle of daylight and darkness. In the following chapter, we will examine the effects that this daily variation in solar heating has on the atmosphere.

The other motion of Earth, **revolution,** refers to its movement in orbit around the Sun. Hundreds of years ago most people believed that Earth was stationary in space. The reasoning was that if Earth was moving, people would

FIGURE 2-1 The Sun over a snow-covered Norwegian landscape. *(Photo by Per Breiehagen/Getty Images)*

feel the movement of the wind rushing past them. Today we know that Earth is traveling at nearly 113,000 kilometers (70,000 miles) per hour in a slightly elliptical orbit about the Sun. Why don't we feel the air rushing past us? The answer is that the atmosphere, bound by gravity to Earth, is carried along at the same speed as Earth.

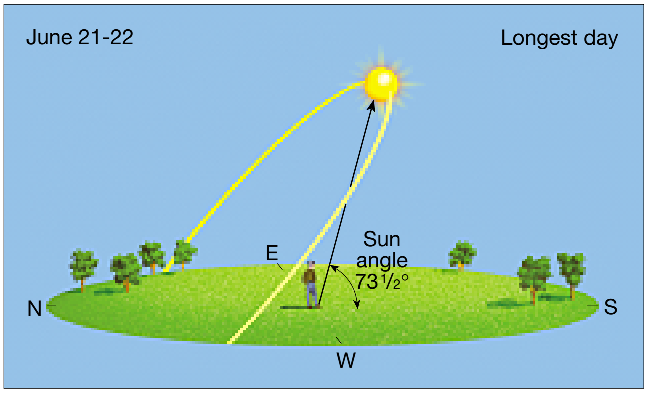
The distance between Earth and Sun averages about 150 million kilometers (93 million miles). Because Earth's orbit is not perfectly circular, however, the distance varies during the course of a year. Each year, on about January 3, our planet is about 147.3 million kilometers (91.5 million miles) from the Sun, closer than at any other time. This position is called the **perihelion.** About six months later, on July 4, Earth is about 152.1 million kilometers (94.5 million miles) from the Sun, farther away than at any other time. This position is called the **aphelion.** Although Earth is closest to the Sun and thus receives more energy in January than in July, this difference plays only a minor role in producing seasonal temperature variations. As proof, consider that Earth is closest to the Sun during the Northern Hemisphere winter.

The Seasons

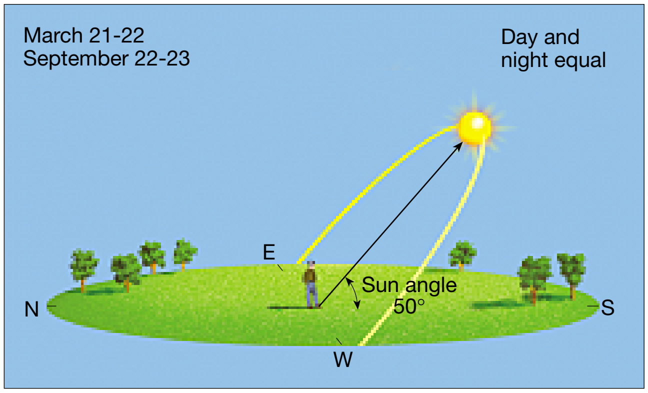
We know that it is colder in winter than in summer, but if variations in the distance between the Sun and Earth do not cause this seasonal temperature change, what does? We adjust to the continuous changes in the duration of daylight that occur throughout the year by planning our outdoor activities accordingly. The gradual but significant *change in day length* certainly accounts for some of the difference we notice between summer and winter. Furthermore, a gradual change in the angle of the noon Sun above the horizon is quite noticeable (Figure 2–2). At midsummer the noon Sun is seen high above the horizon. 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° angle), the solar rays are most concentrated. The lower the angle, the more spread out and less intense is the solar radiation that reaches the surface. This idea is illustrated in Figure 2–3. You have probably experienced this when using a flashlight. If the beam strikes a surface perpendicularly, a small intense spot is produced. When the flashlight beam strikes the object at an oblique angle, however, the area illuminated is larger—and dimmer.

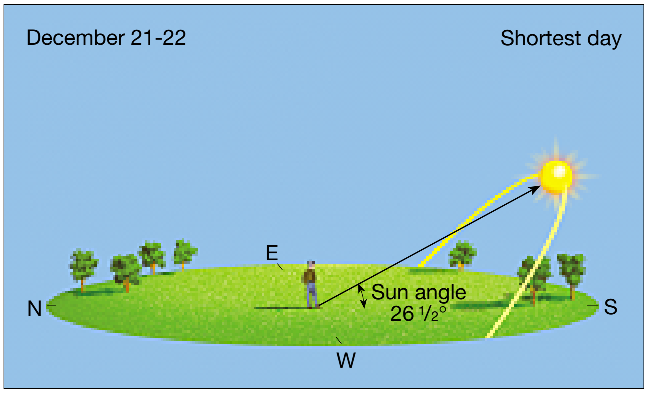
Second, and of less importance, the angle of the Sun determines the thickness of atmosphere that the rays must penetrate (Figure 2–4). When the Sun is directly overhead, the rays pass through a thickness of only 1 atmosphere. But rays entering at a 30° angle travel through twice this amount, and 5° rays travel through a thickness roughly equal to 11 atmospheres (Table 2–1). The longer the path, the greater is the chance that sunlight will be absorbed, reflected, or scattered by the atmosphere, all of which reduce the intensity at the surface. These same effects account for the fact that we cannot look directly at the midday Sun but we can enjoy gazing at a sunset.



(a) Summer solstice



(b) Spring or fall equinox



(c) Winter solstice

FIGURE 2-2 Daily paths of the Sun for a place located at 40°N 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 $73\frac{1}{2}$ to $26\frac{1}{2}$ degrees—a difference of 47 degrees (see Figure 2-6). Notice also how the location of sunrise (east) and sunset (west) changes during a year.

It is important to remember that Earth has a spherical shape. Hence, on any given day, only places located along a particular latitude will receive vertical (90°) rays from the Sun. As we move either north or south of this location, the Sun's rays strike at an ever decreasing angle. Thus, the nearer a place is situated to the latitude receiving the vertical rays of the Sun, the higher will be its noon Sun, and the more concentrated will be the radiation it receives.

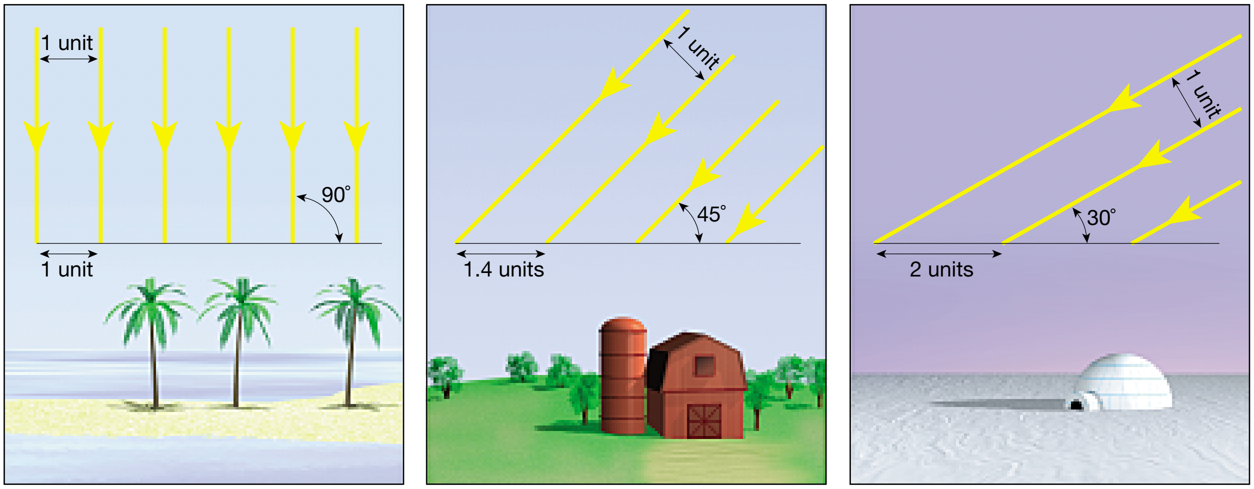


FIGURE 2-3 Changes in the Sun's angle cause variations in the amount of solar energy reaching Earth's surface. The higher the angle, the more intense the solar radiation.

In summary, the most important reasons for the variation in the amount of solar energy reaching a particular location are the seasonal changes in the angle at which the Sun's rays strike the surface and in the length of daylight.

Earth's Orientation

What causes the fluctuations in the Sun's angle and length of daylight that occur during the course of a year? They occur *because Earth's orientation to the Sun continually changes.* 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, which is called the **plane of the ecliptic.** Instead, it is tilted 23 1/2° from the perpendicular, as shown in Figure 2–4. This is called the **inclination of the axis.** As we shall see, if the axis were not so inclined, we would have no seasonal changes. In addition, because the axis remains pointed in the same direction (toward the North Star) as Earth journeys around the Sun, the orientation of Earth's axis to the Sun's rays is constantly changing (Figure 2–5).

For example, on one day in June each year, Earth's position in orbit is such that the Northern Hemisphere is "leaning" 23 1/2° *toward* the Sun (left in Figure 2–5). Six months later, in December, when Earth has moved to the opposite side of its orbit, the Northern Hemisphere "leans" 23 1/2° *away* from the Sun (Figure 2–5, right). On days between these extremes, Earth's axis is leaning at amounts less than 23 1/2° 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 23 1/2° north of the equator to 23 1/2° south of the equator. In turn, this migration causes the angle of the noon Sun to vary by up to 47° (23 1/2 + 23 1/2) for many locations during a year. A mid-

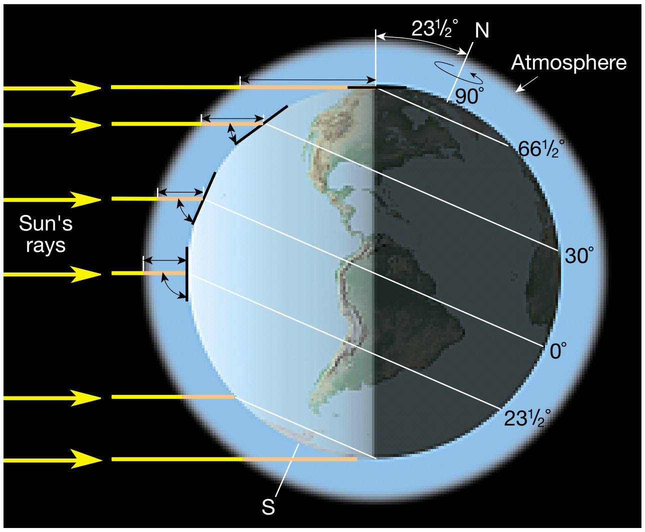


FIGURE 2-4 Rays striking Earth at a low angle (toward the poles) must traverse more of the atmosphere than rays striking at a high angle (around the equator) and thus are subject to greater depletion by reflection and absorption.

TABLE 2-1 Distance radiation must travel through the atmosphere

Angle of Sun above horizon	Equivalent number of atmospheres sunlight must pass through
90° (Directly overhead)	1.00
80°	1.02
70°	1.06
60°	1.15
50°	1.31
40°	1.56
30°	2.00
20°	2.92
10°	5.70
5°	10.80
0° (At horizon)	45.00

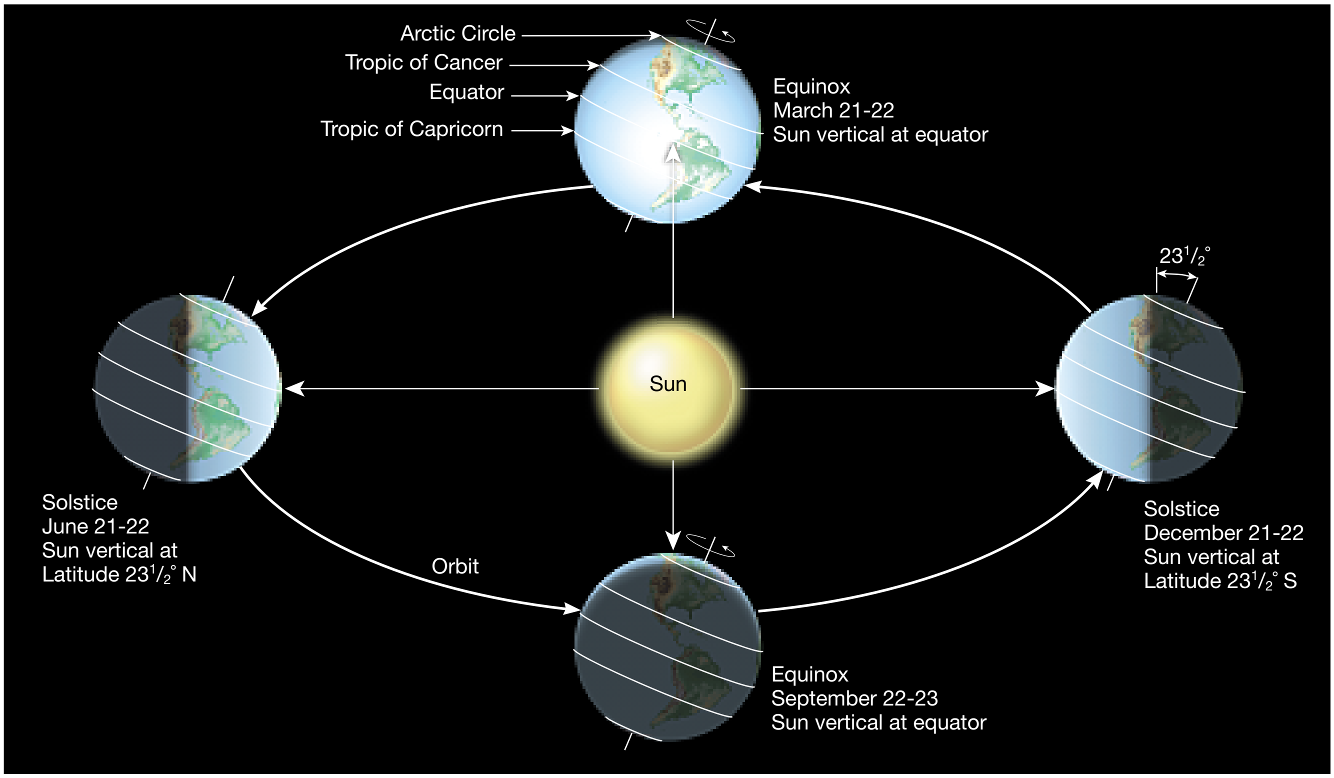


FIGURE 2-5 Earth–Sun relationships.

latitude city like New York, for instance, has a maximum noon Sun angle of 73 1/2° when the Sun's vertical rays have reached their farthest northward location in June and a minimum noon Sun angle of 26 1/2° six months later (Figure 2–6).

Students Sometimes Ask…

Does the Sun get directly overhead anywhere in the United States?

Yes, but only in the state of Hawaii. Honolulu, located on the island of Oahu at about 21° north latitude, experiences a 90° Sun angle twice each year—once at noon on about May 27 and again at noon on about July 20. All of the other states are located north of the Tropic of Cancer and therefore never experience the vertical rays of the Sun.

Solstices and Equinoxes

Historically, four 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 cycle of weather. On June 21 or 22, Earth is in a position where the axis in the Northern Hemisphere is tilted 23 1/2° toward the Sun (Figure 2–5). At this time the vertical rays of the Sun are striking 23 1/2° north latitude (23 1/2° north of the equator), a line of latitude known as the **Tropic of Cancer.** For people living in the Northern Hemisphere, June 21 or 22 is known as the **summer solstice,** the first "official" day of summer (see Box 2–1).

Six months later, on about December 21 or 22, Earth is in an opposite position, where the Sun's vertical rays are striking at 23 1/2° south latitude. This line is known as the **Tropic of Capricorn.** For those of us in the Northern Hemisphere, December 21 or 22 is the **winter solstice,** the first day of winter. However, at the same time in the Southern Hemisphere, people are experiencing just the opposite—the summer solstice.

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

The length of daylight versus darkness is also determined by the position of Earth in its 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 by examining Figure 2–7, which illustrates the **circle of illumination**—that is, the boundary separating the dark half of Earth from the lighted half. The length of daylight is established by comparing the fraction of a line of latitude that is on the "day" side of the circle of illumination with the fraction on the "night" side. Notice that on June 21 all locations in the Northern Hemisphere experience longer periods

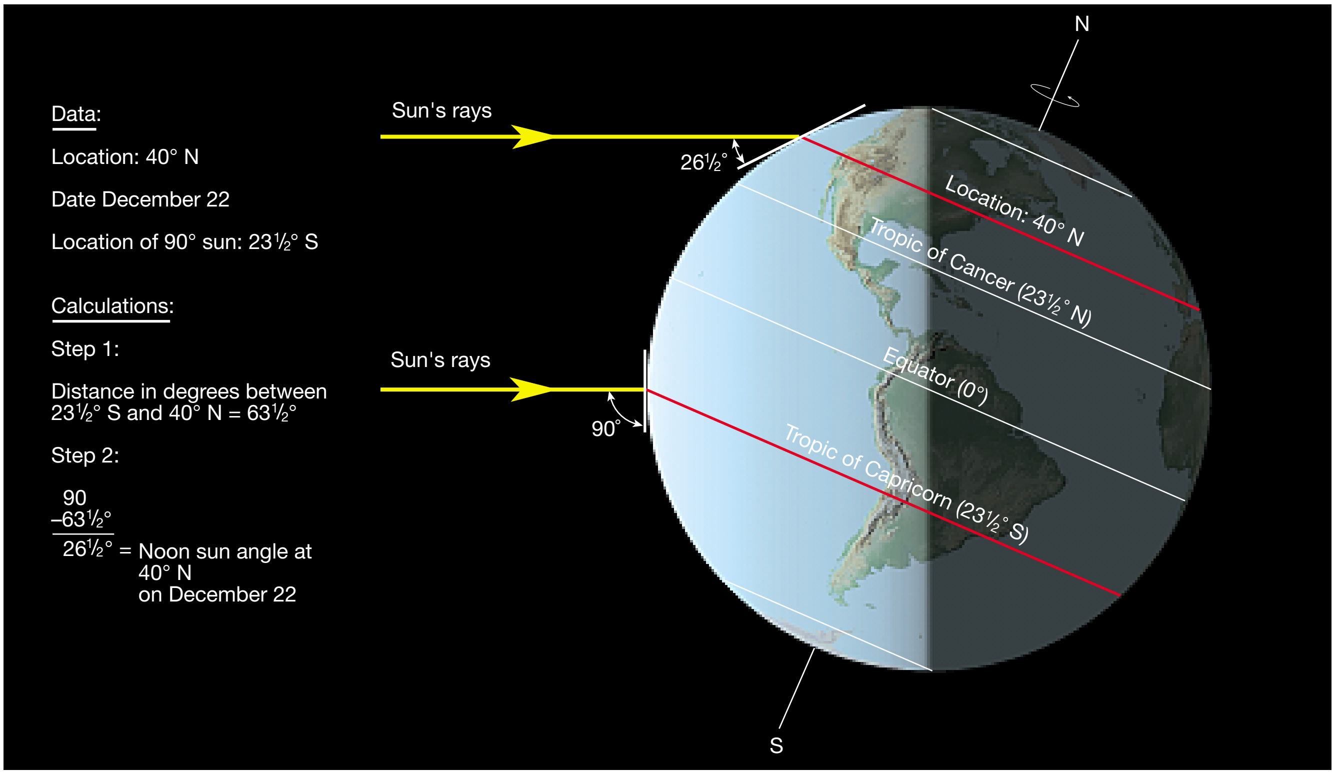


FIGURE 2-6 Calculating the noon Sun angle. Recall that on any given day, only one latitude receives vertical (90°) rays of the Sun. A place located 1° away (either north or south) receives an 89° angle; a place 2° away, an 88° angle, and so forth. To calculate the noon Sun angle, simply find the number of degrees of latitude separating the location you want to know about from the latitude that is receiving the vertical rays of the Sun. Then subtract that value from 90°. The example in this figure illustrates how to calculate the noon Sun angle for a city located at 40° north latitude on December 22 (winter solstice).

of daylight than darkness (Figure 2–7). The opposite is true for the December solstice, when the length of darkness exceeds the length of daylight at all locations in the Northern Hemisphere. Again, for comparison, let us consider New York City (about 40°N). It has 15 hours of daylight on June 21 and only nine hours on December 21.

Also note, from Table 2–2, that the farther north you are of the equator on June 21, the longer the period of daylight. When you reach the Arctic Circle (66 1/2°N), the length of daylight is 24 hours. This is the "midnight Sun," which does not set for about six months at the North Pole (Figure 2–8).

TABLE 2-2 Length of daylight

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

As a review of the characteristics of the summer solstice for the Northern Hemisphere, examine Figure 2–7 and Table 2–2 and consider the following facts:

1. The date of occurrence is June 21 or 22.
2. The vertical rays of the Sun are striking the Tropic of Cancer (23 1/2° north latitude).
3. Locations in the Northern Hemisphere are experiencing their longest length of daylight and highest Sun angle (opposite for the Southern Hemisphere).
4. The farther north you are of the equator, the longer the period of daylight until the Arctic Circle is reached, where the length of daylight becomes 24 hours long (opposite for the Southern Hemisphere).

The facts about the winter solstice are just the opposite. It should now be apparent why a midlatitude location is warmest in the summer. It is then that the days are longest and the angle of the Sun is highest (see Box 2–2).

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, thus dividing the latitudes in half.

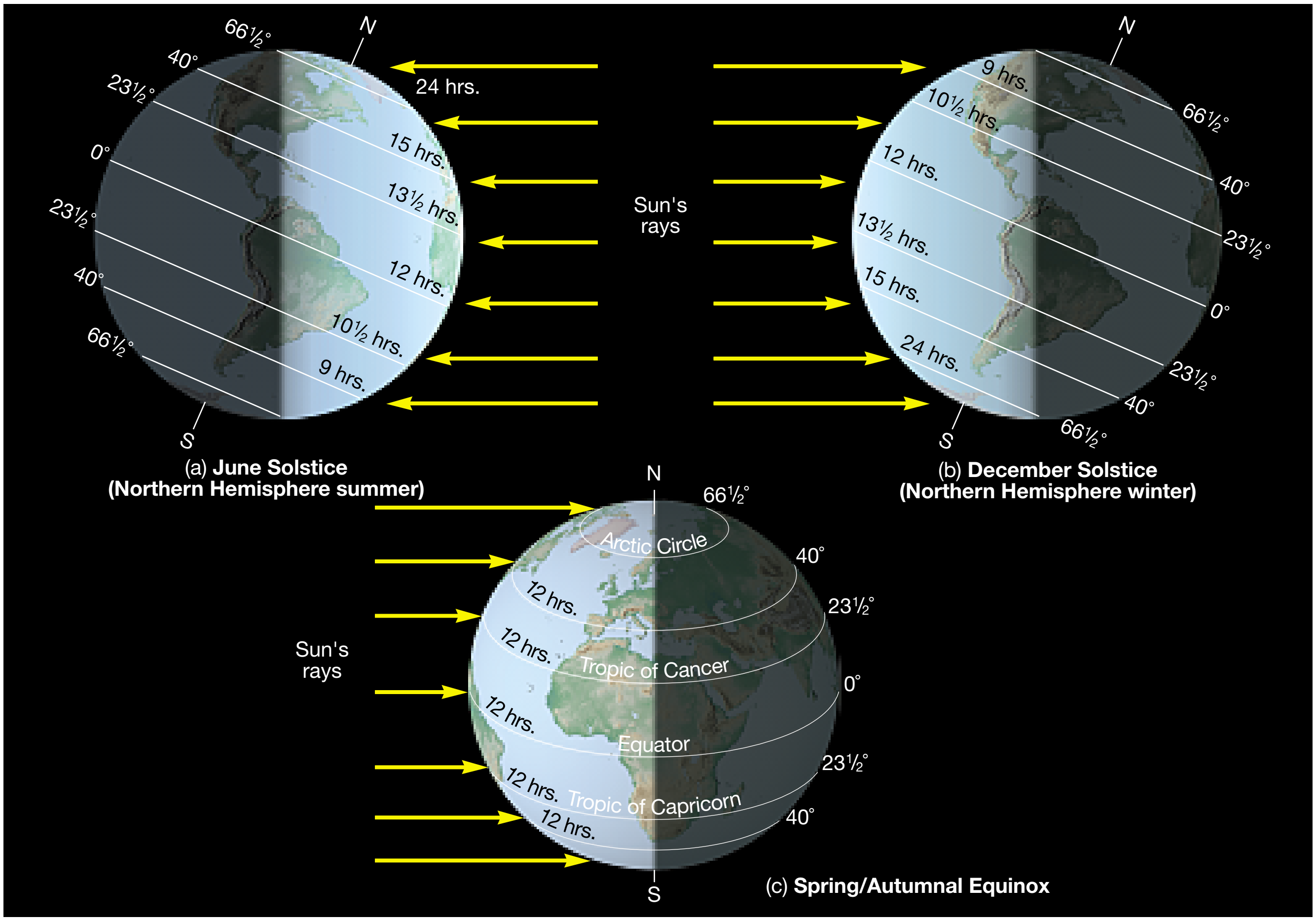


FIGURE 2-7 Characteristics of the solstices and equinoxes.

FIGURE 2-8 Multiple exposures of the midnight Sun in late June or July in high northern latitudes—Alaska, Scandinavia, Northern Canada, etc. *(Photo by Brian Stablyk/Getty Images, Inc./Stone Allstock)*

BOX 2-1 When Are the Seasons?

Have you ever been caught in a snowstorm around Thanksgiving, only to be told by the TV weatherperson that winter does not begin until December 21? Or perhaps you have endured several consecutive days of 100° temperatures only to discover that summer has not "officially" started? The idea of dividing the year into four seasons clearly originated from the Earth–Sun relationships discussed in this chapter (Table 2–A). This astronomical definition of the seasons defines winter (Northern Hemisphere) as the period from the winter solstice (December 21–22) to the spring equinox (March 21–22) and so forth. This is also the definition used most widely by the news media, yet it is not unusual for portions of the United States and Canada to have significant snowfalls weeks before the "official" start of winter (Figure 2–A).

TABLE 2-A Occurrence of the seasons in the Northern Hemisphere

Season	Astronomical season	Climatological season
Spring	March 21 or 22 to June 21 or 22	March, April, May
Summer	June 21 or 22 to September 22 or 23	June, July, August
Autumn	September 22 or 23 to December 21 or 22	September, October, November
Winter	December 21 or 22 to March 21 or 22	December, January, February

Because the weather phenomena we normally associate with each season do not coincide well with the astronomical seasons, meteorologists prefer to divide the year into four three-month periods based primarily on temperature. Thus, winter is defined as December, January, and February, the three coldest months of the year in the Northern Hemisphere. Summer is defined as the three warmest months, June, July, and August. Spring and autumn are the transition periods between these two seasons. Inasmuch as these four three-month periods better reflect the temperatures and weather that we associate with the respective seasons, this definition of the seasons is more useful for meteorological discussions.

FIGURE 2-A Fall scene in the Adirondacks of upstate New York. *(Photo by Kim Heacox Photography/DRK Photo)*

In summary, *seasonal fluctuations in the amount of solar energy reaching various places on Earth's surface are caused by the migrating vertical rays of the Sun and the resulting variations in Sun angle and length of daylight.* These changes in turn cause the month-to-month variations in temperature observed at most locations outside the tropics. Figure 2–9 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 situated 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, such is not the case. Although the angle of the Sun above the horizon and the length of daylight are the main controls of temperature, they are not the only controls, as we shall see in Chapter 3.

Students Sometimes Ask…

Where is the Land of the Midnight Sun?

Anyplace located north of the Arctic Circle (66 1/2° N) or south of the Antarctic Circle (66 1/2° S) experiences 24 hours of continuous daylight (or darkness) at least one day each year. The closer a place is to a pole, the longer the period of continuous daylight (or darkness). Someone stationed at either pole will experience six months of continuous daylight followed by six months of darkness. Thus, the Land of the Midnight Sun refers to any location where the latitude is greater than 66 1/2°, such as the northern portions of Alaska, Canada, Russia, Scandinavia, as well as practically all of Antarctica.

Energy, Heat, and Temperature

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. Energy comes to Earth from the Sun in the form of electromagnetic radiation, which we see as light and feel as heat. There are countless places and situations where energy is present. We find it in the food we eat, the water located at the top of a falls, and the waves that break along the shore.

For our purposes we will define **energy** simply as *the capacity to do work*. We can think of work as being done whenever matter is moved. Everyday examples include the chemical energy from gasoline that powers an automobile, the heat energy from a stove that excites water molecules (boils water), and the gravitational energy that has the capacity to move snow down a mountain slope in the form of an avalanche. These examples illustrate that energy takes many forms. Moreover, energy can change from one form to another. For example, the chemical energy in gasoline is first converted to heat in the engine of an automobile, which is then converted to mechanical energy that moves the automobile along.

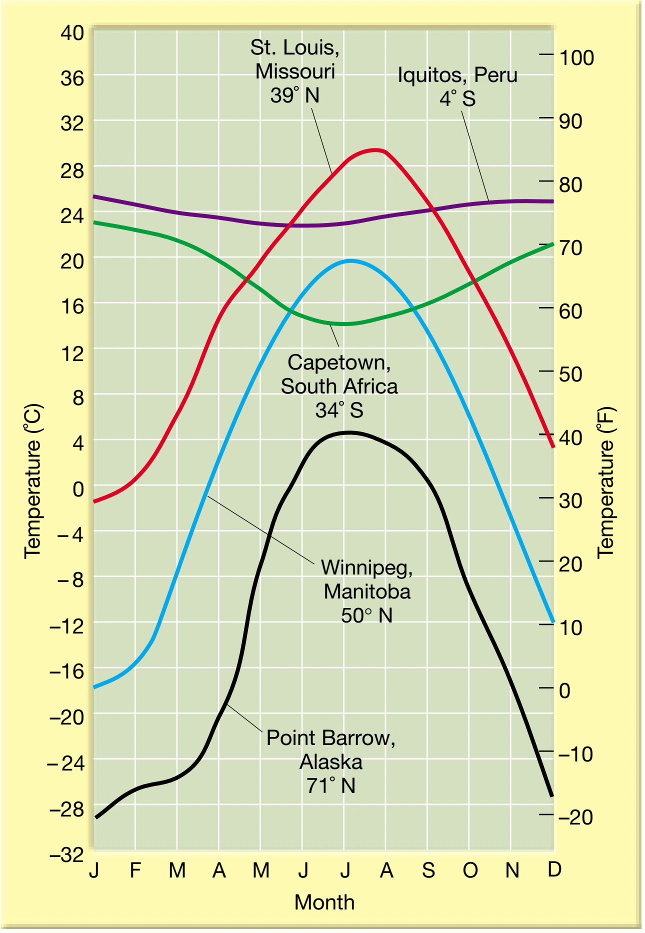


FIGURE 2-9 Mean monthly temperatures for six cities located at different latitudes. Note that Capetown, South Africa, experiences winter in June, July, and August.

Forms of Energy

You are undoubtedly familiar with some of the common forms of energy, such as heat, chemical, nuclear, radiant (light), and gravitational energy. In addition, some forms of energy are classified into two major categories: *kinetic energy* and *potential energy*.

Kinetic Energy. *Energy associated with an object by virtue of its motion* is described as **kinetic energy.** A simple example of kinetic energy is the motion of a hammer when driving a nail. Because of its motion, the hammer is able to move another object (do work). The faster the hammer is swung, the greater its kinetic energy (energy of motion). Similarly, a larger (more massive) hammer will possess more kinetic energy than a smaller one, provided both are swung at the same velocity. Likewise, the winds associated with a hurricane possess much more kinetic energy than do light, localized breezes. Hurricane-force winds are both larger in scale (more massive) and travel at higher velocities.

Kinetic energy is also significant at the atomic level. All matter is composed of atoms and molecules that are continually vibrating. Thus, by virtue of this motion, the atoms or molecules in matter have kinetic energy. When a pan of water is placed over a fire, the water becomes warmer, because the heat from the fire causes the water molecules to vibrate faster. We can conclude that when a solid, liquid, or gas is heated, its atoms or molecules move faster and possess more kinetic energy.

Potential Energy. As the term implies, **potential energy** has the potential to do work. For example, large hailstones suspended by an updraft in a towering cloud have potential energy because of their position. Should the updraft subside, these hailstones could do destructive work on someone's roof. Many substances, including wood, gasoline, and the food you eat, contain potential energy, which is capable of doing work given the right circumstances.

Temperature

Temperature is a quantity that describes how warm or cold an object is with respect to some standard measure. In the United States the Fahrenheit scale is used most often for everyday expressions of temperature. However, laboratories and most of the rest of the world use the Celsius and Kelvin temperature scales. A discussion of these scales is provided in Chapter 3.

Temperature can also be described as a *measure of the average kinetic energy of the atoms or molecules in a substance.* When a substance gains energy, its particles move faster and its temperature rises. By contrast, when energy is lost, the atoms and molecules vibrate more slowly and its temperature drops.

It is important to note that temperature is *not* a measure of the total kinetic energy of the particles within a substance. For example, a cup of boiling water has a higher temperature than a tub of lukewarm water. However, the quantity of water in the cup is small, so it contains far less kinetic energy than the water in the tub. Much more ice would melt in the tub of lukewarm water than in the cup of boiling water. The temperature of the water in the cup is higher because the atoms and molecules are vibrating faster, but the total amount of kinetic energy is much smaller because there are many fewer particles.

Heat

When you touch a hot stove, heat enters your hand because the stove is warmer than your hand. By contrast, when you hold an ice cube, heat is transferred from your hand to the ice cube. The transfer of energy into or out of an object because of temperature differences between that object and its surroundings is called **heat.** Heat flows from a region of higher temperature to one of lower temperature. Once the temperatures become equal, heat flow stops.

When an object absorbs heat, it appears as an increase in internal energy, often in the form of increased molecular motion. (Sometimes, as when ice melts, a substance absorbs heat without an increase in kinetic energy, a topic we shall consider in Chapter 4.) However, we do not say that a substance has heat, because heat describes energy that is flowing or being transferred. We can examine the flow of energy between substances of different temperatures by imagining a warm bottle of wine placed in a bucket of chilled water. According to the concept of kinetic energy, the average speed of the molecules in the bottle of wine is greater than those in the cold water. As the molecules collide with the sides of the wine bottle, the faster molecules (warm wine) tend to slow down, while the slower molecules (cold water) tend to speed up. Assuming no other source of energy, the average speed of the molecules in these liquids (and therefore their temperatures) eventually becomes equal. The net result is that energy has flowed from the warm wine to the cold water. So heat can be thought of as internal energy of matter that transfers from one thing to another by virtue of a temperature difference.

Students Sometimes Ask…

What would the seasons be like if Earth was not tilted on its axis?

The most obvious change would be that all locations on the globe would experience 12 hours of daylight every day of the year. Moreover, for any latitude, the Sun would always follow the path it does during an equinox. There would be no seasonal temperature changes, and daily temperatures would be roughly equivalent to the "average" for that location.

Mechanisms of Heat Transfer

Heating Earth's Surface and Atmosphere

▶ Solar Radiation

As we consider heat-transfer mechanisms, recall that heat flows from warmer substances to cooler substances. If two objects are in contact, the one that is warmer will become cooler and the cooler one will become warmer, until they reach a common temperature. This flow of energy called *heat* can occur in three ways: *conduction, convection,* and *radiation* (Figure 2-10). Although they are presented separately, all three mechanisms of heat transfer can operate simultaneously. In addition, these processes transfer heat between the Sun and Earth and between Earth's surface, the atmosphere, and outer space.

Conduction

Conduction is familiar to most of us through our everyday experiences. Anyone who has attempted to pick up a metal spoon that was left in a boiling pot of soup realized that heat was transmitted along the entire length of the spoon. The transfer of heat in this manner is called conduction. The hot soup caused the molecules at the lower end of the spoon to

BOX 2-2 The Analemma

The analemma is a graph resembling a figure 8 that can be used as a reference when calculating the angle of noon Sun for any location on the globe, for any day of the year. An analemma shows the latitude where the noon Sun is directly overhead (90-degree angle) for each day of the year. Notice that on March 21–22 and September 21–22 the Sun is directly overhead at the equator, a fact we considered earlier (Figure 2-B).

By knowing where the noon Sun is overhead, you can readily calculate the angle of the noon Sun at any other latitude for any date. For each degree of latitude that a particular location is from the latitude where the Sun is overhead, the angle of the noon Sun at that location is one degree less than 90 degrees. For example, if you want to know the angle of the noon Sun at New York City (40°N) on May 14, you first find that date on the analemma to establish the latitude where the noon Sun is directly overhead. In this case it is 18 degrees north latitude. *It is important to note whether the location is north or south of the equator.* Thus, New York City is 22 degrees (40° N − 18° N = 22°) from the location where the Sun is directly overhead on May 14. Consequently, the angle of the noon Sun at New York City on May 14 is 68 degrees above the horizon. (Note that New York is 22 degrees from the location where the Sun is directly overhead. Subtracting that figure from 90 degrees yields 68 degrees [90 − 22 = 68]). Can you calculate the noon Sun angle for a place located at 40°S latitude on May 14? (*Hint:* See Figure 2-6.)

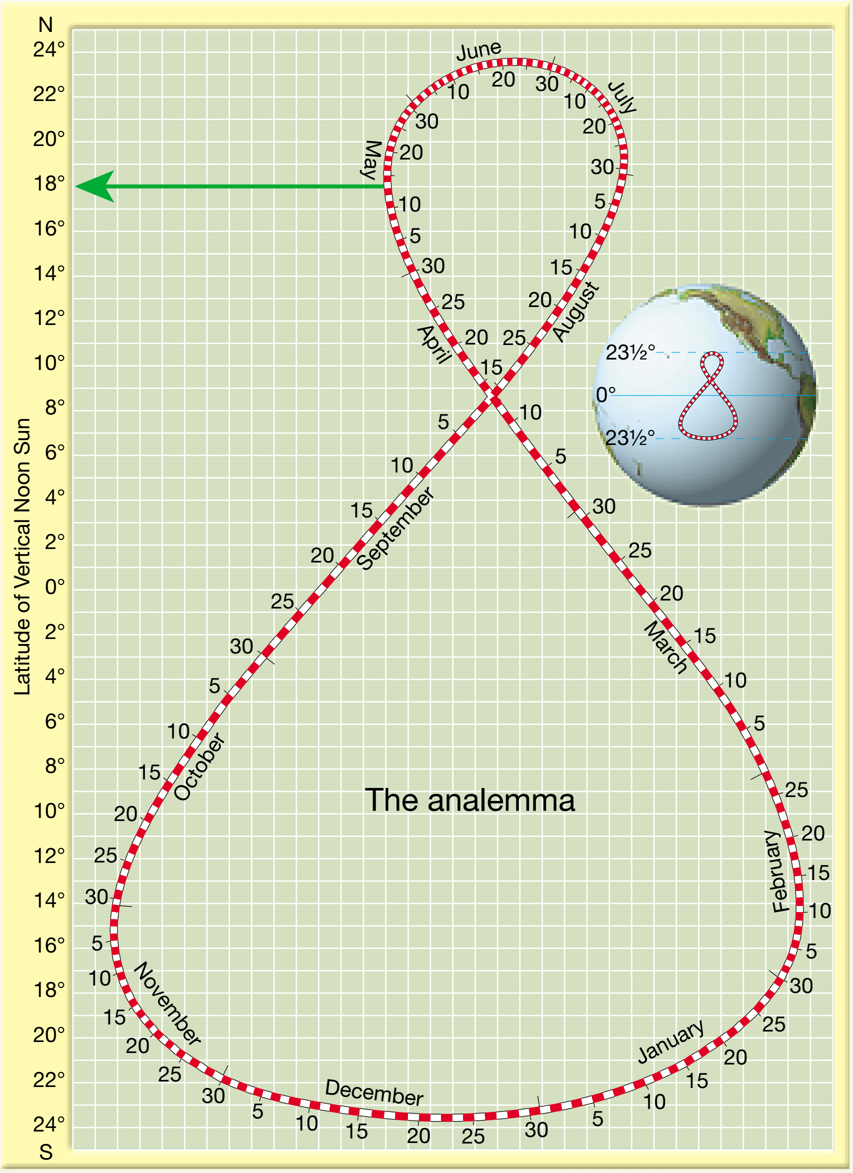


FIGURE 2-B The analemma, a graph showing the latitude of the overhead (vertical) noon Sun throughout the year.

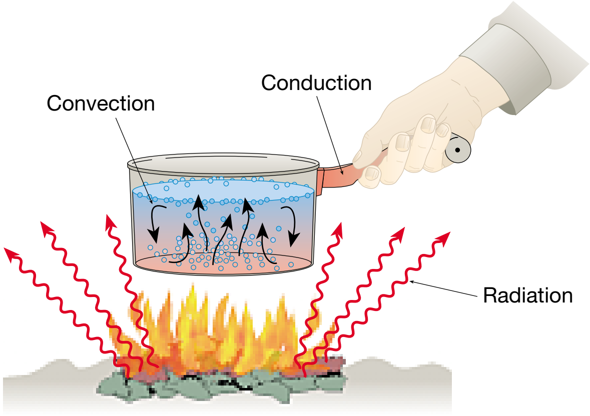


FIGURE 2-10 The three mechanisms of heat transfer: conduction, convection, and radiation.

vibrate more rapidly. These molecules and free electrons collided more vigorously with their neighbors and so on up the handle of the spoon. Thus, **conduction** is the transfer of heat through electron and molecular collisions from one molecule to another. The ability of substances to conduct heat varies considerably. Metals are good conductors, as those of us who have touched a hot spoon have quickly learned. Air, in contrast, is a very poor conductor of heat. Consequently, conduction is important only between Earth's surface and the air immediately in contact with the surface. As a means of heat transfer for the atmosphere as a whole, conduction is the least significant and can be disregarded when considering most meteorological phenomena.

Objects that are poor conductors, like air, are called *insulators*. Most objects that are good insulators, such as cork, plastic foams, or goose down, contain many small air spaces. It is the poor conductivity of the trapped air that gives these materials their insulating value. Snow is also a poor conductor (good insulator). Like other insulators, fresh snow contains numerous air spaces that serve to retard the flow of heat. Thus, a wild animal will often burrow into a snowbank to escape the "cold." The snow, like a down-filled comforter, does not supply heat; it simply retards the loss of the animal's own body heat.

Students Sometimes Ask…

In the morning when I get out of bed, why does the tile flooring in the bathroom feel much colder than the carpeted area, even though both materials are the same temperature?

The difference you feel is due mainly to the fact that floor tile is a much better conductor of heat than carpet. Hence, heat is more rapidly conducted from your bare feet when you are standing on the tile floor than when you are on the carpeted floor. Even at room temperature (20°C or 68°F), objects that are good conductors can feel chilly to the touch. (Remember, body temperature is about 98.6°F.)

Convection

Much of the heat transport that occurs in the atmosphere and ocean is carried on by convection. **Convection** is heat transfer that involves the actual movement or circulation of a substance. It takes place in fluids (liquids like water and gases like air) where the material is able to flow. Because the atoms or molecules in solids vibrate around a fixed point, heat transfer in solids takes place by conduction.

The pan of water being heated over a campfire in Figure 2-10 illustrates the nature of a simple convective circulation. The fire warms the bottom of the pan, which conducts heat to the water inside. Because water is a relatively poor conductor, only the water in close proximity to the bottom of the pan is heated by conduction. Heating causes water to expand and become less dense. Thus, the buoyant water near the bottom of the pan rises while the cooler, denser water above sinks. As long as the water is heated from the bottom and cools near the top, it will continue to "turn over," producing a *convective circulation.*

In a similar manner, much of the heat acquired in the lowest layer of the atmosphere by way of radiation and conduction is transported by convection. For example, on a hot, sunny day the air above a large asphalt parking lot will be heated more than the air above the surrounding woodlands. As warm, less dense air buoys upward, it transports heat to greater heights. These movements, called **thermals,** are what hang-glider pilots use to keep their crafts soaring. Convection not only transfers heat but also transports moisture aloft. The result is an increase in cloudiness that frequently can be observed on warm summer afternoons.

On a much larger scale is the global circulation of the atmosphere, which is driven by the unequal heating of Earth's surface. These complex movements are responsible for the redistribution of heat between hot equatorial regions and frigid polar latitudes and will be discussed in detail in Chapter 7.

Atmospheric circulation consists of vertical as well as horizontal components, so both vertical and horizontal heat transfer occurs. Meteorologists often use the term *convection* to describe that part of the atmospheric circulation that involves *upward and downward* heat transfer. By contrast, the term **advection** is used to denote the horizontal component of convective flow. (The common term for advection is "wind," a phenomenon we will examine closely in later chapters.) Those who reside in the midlatitudes often experience the effects of heat transfer by advection. For example, when frigid Canadian air invades the Midwest in January, it brings bitterly cold winter weather. By contrast, the northward flow of air from the Gulf of Mexico is associated with warm temperatures.

Radiation

The third mechanism of heat transfer is radiation. Unlike conduction and convection, which need a medium in which to travel, radiant energy does not. Radiation is the only mechanism of heat transfer that travels through the vacuum of space. Therefore, it is the heat-transfer mechanism by which solar energy reaches our planet.

Solar Radiation. As noted earlier, the Sun is the ultimate source of energy that drives the weather machine. For this reason, we consider the nature of solar radiation in more detail. From our everyday experience, we know that the Sun emits light and heat as well as the rays that give us a suntan. Although these forms of energy constitute a major portion of the total energy that radiates from the Sun, they are only a part of a large array of energy called **radiation** or **electromagnetic radiation.** This array or spectrum of electromagnetic energy is shown in Figure 2-11.

All types of radiation, whether X rays, radio waves or heat waves, travel through the vacuum of space at 300,000 kilometers (186,000 miles) per second, a value known as the *speed of light.* To help visualize radiant energy, imagine ripples made in a calm pond when a pebble is tossed in. Like the waves produced in the pond, electromagnetic waves come in various sizes or **wavelengths**—the distance from one crest to the next (Figure 2-11). Radio waves have the longest wavelengths, up to tens of kilometers in length. Gamma waves are the shortest, being less than a billionth of a centimeter long. Visible light is roughly in the middle of this range.

Radiation is often identified by the effect that it produces when it interacts with an object. The retinas of our eyes, for instance, are sensitive to a range of wavelengths that we call **visible light.** We often refer to visible light as white light, for it appears "white" in color. It is easy to show, however, that white light is really an array of colors, each color corresponding to a specific range of wavelengths. By using a prism, white light can be divided into the colors of the rainbow, from violet with the shortest wavelength, 0.4 micrometer (1 micrometer is 0.001 centimeter), to red with the longest wavelength, 0.7 micrometer.

Located adjacent to the color red, and having a longer wavelength, is **infrared radiation,** which we cannot see but our skin detects as heat. (Only the infrared energy that is nearest the visible part of the spectrum is intense enough to be felt as heat.) The invisible waves located next to violet are called **ultraviolet radiation.** These are the wavelengths that are responsible for sunburn (see Box 2-3).

Although we divide radiant energy into categories based on our ability to perceive them, all wavelengths of radiation behave in a similar manner. When an object absorbs any form of electromagnetic energy, the waves excite subatomic particles (electrons), which results in an increase in molecular motion and a corresponding increase in temperature. Thus, the rapid vibrations of extremely hot molecules on the Sun create electromagnetic waves that travel through space and, upon being absorbed, increase the molecular motion of other groups of molecules—including those that make up the atmosphere, Earth's land-sea surface, and even our bodies.

One important difference among the various wavelengths of radiant energy is that shorter wavelengths are more energetic. This accounts for the fact that relatively short (high-energy) ultraviolet waves can damage human tissue more readily than similar exposures to longer wavelength radiation. The damage can result in skin cancer and cataracts.

It is important to note that the Sun emits all forms of radiation, as shown in Figure 2-11, but in varying quantities. Over 95 percent of all solar radiation is emitted in wavelengths between 0.1 and 2.5 micrometers, with much of this energy concentrated in the visible and near-visible parts of the electromagnetic spectrum (Figure 2-12). The narrow band of visible light, between 0.4 and 0.7 micrometer, represents over

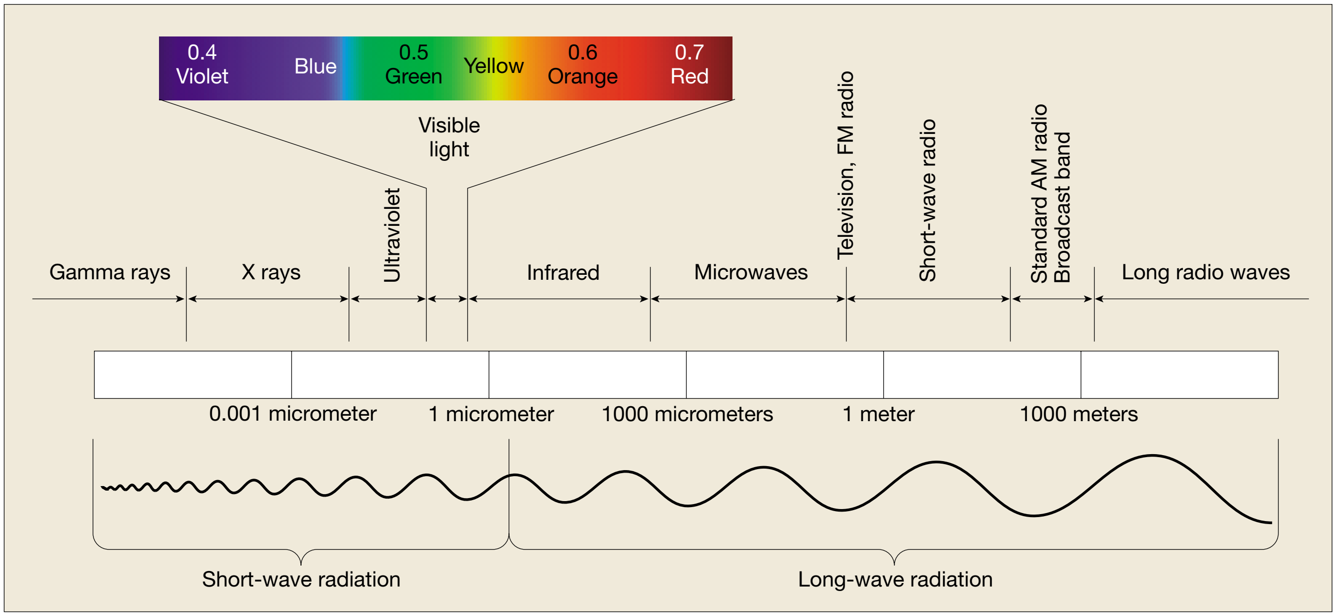


FIGURE 2-11 The electromagnetic spectrum, illustrating the wavelengths and names of various types of radiation.

BOX 2-3 The Ultraviolet Index

*Gong-Yuh Lin**

TABLE 2-B The UV Index: Minutes to burn for the most susceptible skin type.

UVI value	Exposure category	Description	Minutes to burn
0–2	Low	Low danger from the Sun's UV rays for the average person.	> 60
3–5	Moderate	Moderate risk from unprotected Sun exposure. Take precautions during the mid-day when Sun is strongest.	40–60
6–7	High	Protection against sunburn is needed. Cover up, wear a hat and sunglasses, and use sunscreen.	25–40
8–10	Very High	Try to avoid the Sun between 11 AM and 4 PM. Otherwise, cover up and use sunscreen.	10–25
11–12	Extreme	Take all precautions. Unprotected skin will burn in minutes. Do not pursue outdoor activities if possible. If out of doors, apply sunscreen liberally every 2 hours.	< 10

Most people welcome sunny weather. On warm days, when the sky is cloudless and bright, many spend a great deal of time outdoors "soaking up" the sunshine (Figure 2-C). The goal is to develop a dark tan, one that sunbathers often describe as "healthy-looking." Ironically, there is strong evidence that too much sunshine (specifically, too much ultraviolet radiation) can lead to serious health problems, mainly skin cancer and cataracts.

Since June 1994 the National Weather Service (NWS) has issued the next-day ultraviolet index (UVI) for the United States to warn the public of potential health risks of exposure to sunlight (Figure 2-D). The UV index is determined by taking into account the predicted cloud cover and reflectivity of the surface, as well as the Sun angle and atmospheric depth for each forecast location. Because atmospheric ozone strongly absorbs ultraviolet radiation, the extent of the ozone layer is also considered. The UVI values lie on a scale from 0 to 11 and higher, with larger values representing greatest risk.

The U.S. Environmental Protection Agency has established five exposure categories based on UVI values—Low, Moderate, High, Very High, and Extreme (Table 2-B). Precautionary measures have been developed for each category. The public is advised to minimize outdoor activities when the UVI is Very High or Extreme. Sunscreen with a sun-protection factor (SPF) of 15 or higher is recommended for all exposed skin. This is especially important after swimming or while sunbathing, even on cloudy days with the UVI in the Low category.

Table 2-B shows the range of minutes to burn for the most susceptible skin type (pale or milky white) for each exposure category. Note that the exposure that results in sunburn varies from over 60 minutes for the Low category to less than 10 minutes for the Extreme category. It takes approximately five times longer to cause sunburn of the least susceptible skin type, brown to dark. The most susceptible skin type develops red sunburn, painful swelling, and skin peeling when exposed to excessive sunlight. By contrast, the least susceptible skin type rarely burns and shows very rapid tanning response.

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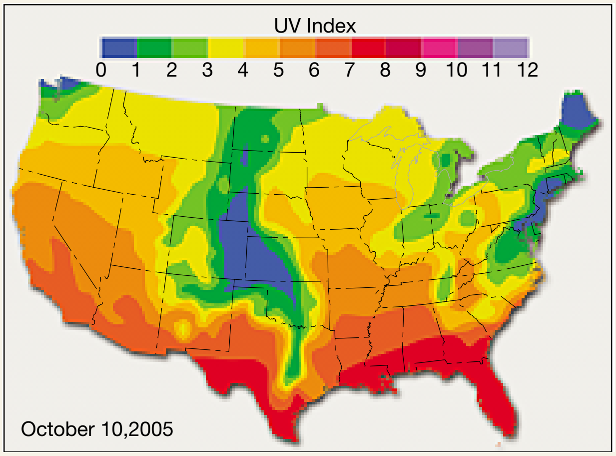
FIGURE 2-C Exposing sensitive skin to too much solar ultraviolet radiation has potential health risks. *(Photo by Eddie Gerald/Rough Guides)*

FIGURE 2-D UV Index forecast for October 10, 2005.



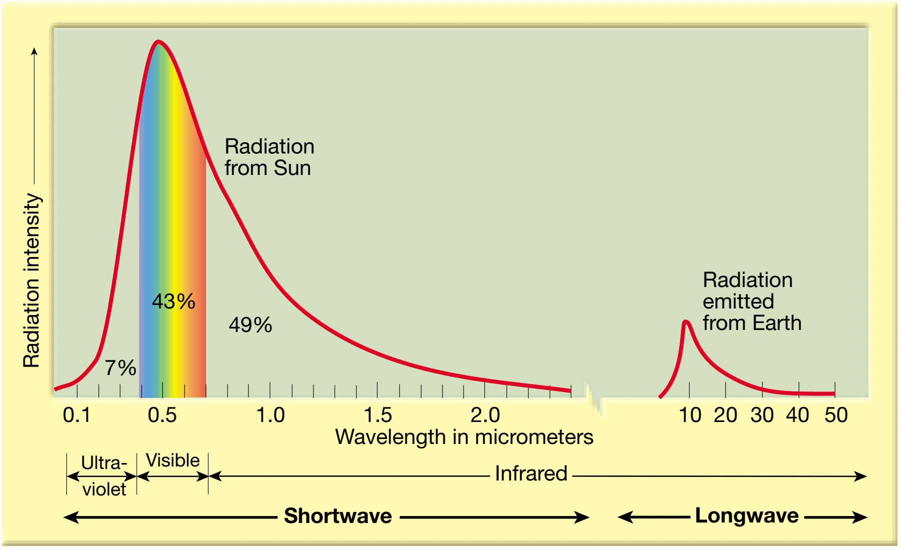


FIGURE 2-12 Comparison of the intensity of solar radiation and radiation emitted by Earth. Because of the Sun's high surface temperature, most of its energy is radiated at wavelengths shorter than 4 micrometers, with the greatest intensity in the visible range of the electromagnetic spectrum. Earth, in contrast, radiates most of its energy in wavelengths longer than 4 micrometers, primarily in the infrared band. Thus, we call the Sun's radiation *shortwave* and Earth's radiation *longwave. (After Tom L. McKnight,* Physical Geography, *© 1990, Prentice Hall, Inc.)*

43 percent of the total energy emitted. The bulk of the remainder lies in the infrared zone (49 percent) and ultraviolet (UV) section (7 percent). Less than 1 percent of solar radiation is emitted as X rays, gamma rays, and radio waves.

Laws of Radiation. To obtain a better appreciation 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 radiation laws. The principles that follow were set forth by physicists during the late 1800s and early 1900s. Although the mathematics of these laws is beyond the scope of this book, the concepts themselves are easy to grasp:

1. **All objects continually emit radiant energy over a range of wavelengths.*** Thus, not only do hot objects like the Sun continually emit energy, but Earth does as well, even its polar ice caps.
2. **Hotter objects radiate more total energy per unit area than do colder objects**. The Sun, which has a surface temperature of 6000 K (10,000°F), emits about 160,000 times more energy per unit area than does Earth, which has an average surface temperature of 288 K (59°F). This concept is called the *Stefan–Boltzman law* and is expressed mathematically in Box 2-4.
3. **The hotter the radiating body, the shorter is the wavelength of maximum radiation.** We can visualize this law by imagining a piece of metal that, when heated sufficiently (as occurs in a blacksmith's shop), produces a white glow. As it cools, the metal 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, the still longer infrared radiation will be detectable as heat. The Sun radiates maximum energy at 0.5 micrometer, which is in the visible range (Figure 2-12). The maximum radiation emitted from 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, it is often referred to as **longwave radiation,** whereas solar radiation is called **shortwave radiation.** This concept is known as *Wien's displacement law* and is expressed mathematically in Box 2-4.
4. **Objects that are good absorbers of radiation are also good emitters.** The perfect absorber (and emitter) is a theoretical object called a **blackbody.** In the visible wavelengths, black coal dust is an excellent absorber (reflects very little light), hence the name blackbody. However, blackbodies do not have to be black in color, they simply must absorb and emit all possible radiation for their respective temperatures. Earth's surface and the Sun approach being blackbodies because they absorb and radiate with nearly 100 percent efficiency. By contrast, the gases that compose our atmosphere are *selective* absorbers and emitters of radiation. For some wavelengths the atmosphere is nearly transparent (little radiation absorbed). For others, however, it is nearly opaque (absorbs most of the radiation that strikes it). Experience tells us that the atmosphere is quite transparent to visible light emitted by the Sun because it readily reaches Earth's surface.

To summarize, although the Sun is the ultimate source of radiant energy, all objects continually radiate energy over a range of wavelengths. Hot objects, like the Sun, emit mostly shortwave radiation. By contrast, most objects at everyday temperatures (Earth's surface and atmosphere) emit mostly longwave (low-energy) radiation. Objects that

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*The temperature of the object must be above a theoretical value called *absolute zero* (−273°C) for it to emit radiant energy. The letter K is used for values on the Kelvin temperature scale. For more explanation, see the section on "Temperature Scales" in Chapter 3.

BOX 2-4 Radiation Laws

*Gregory J. Carbone**

All bodies radiate energy. Both the rate and the wavelength of radiation emission depend on the temperature of the radiating body.

Stefan–Boltzman Law

This law mathematically expresses the rate of radiation emission per unit area:

$$E = \sigma T^4$$

E, the rate of radiation emitted by a body, is proportional to the fourth power of the body's temperature (T). The Stefan–Boltzmann constant (σ) is equal to $5.67 \times 10^{-8}\ \mathrm{W/m^2\,K^4}$. Compare the difference between the radiation emission from the Sun and Earth. The Sun, with an average temperature of 6000 K, emits 73,483,200 watts per square meter ($\mathrm{Wm^{-2}}$):

$$\begin{aligned} E &= (5.67 \times 10^{-8}\ \mathrm{W/m^2\,K^4})\\ &\quad (6000\ \mathrm{K})^4 \\ &= 73{,}483{,}200\ \mathrm{W/m^2} \end{aligned}$$

By contrast, Earth has an average temperature of only 288 K. If we round the value to 300 K, we have

$$\begin{aligned} E &= (5.67 \times 10^{-8}\ \mathrm{W/m^2K^4})\\ &\quad (300\ \mathrm{K})^4 \\ &= 459\ \mathrm{W/m^2} \end{aligned}$$

The Sun has a temperature that is approximately 20 times higher than Earth and thus emits approximately 160,000 times more radiation per unit area. This makes sense because $20^4 = 160{,}000$.

Wien's Displacement Law

This law describes mathematically the relationship between the temperature (T) of a radiating body and its wavelength of maximum emission (λ_{max}):

$$\lambda_{\mathrm{max}} = C/T$$

Wien's constant (C) is equal to 2898 μmK. If we use the Sun and Earth as examples, we find

$$\lambda_{\mathrm{max}}(\mathrm{Sun}) = \frac{2898\ \mu\mathrm{mK}}{6000\ \mathrm{K}} = 0.483\ \mu\mathrm{m}$$

and

$$\begin{aligned} \lambda_{\mathrm{max}}(\mathrm{Earth}) &= \frac{2898\ \mu\mathrm{mK}}{300\ \mathrm{K}} \\ &= 9.66\ \mu\mathrm{m} \end{aligned}$$

Note that the Sun radiates its maximum energy within the visible portion of the electromagnetic spectrum. The cooler Earth radiates its maximum energy in the infrared portion of the electromagnetic spectrum.

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are good absorbers of radiation, like Earth's surface, are also good emitters. By contrast, most gases are only good absorbers (emitters) in certain wavelengths but poor absorbers in other wavelengths.

What Happens to Incoming Solar Radiation?

GEODe ATMOSPHERE **Heating Earth's Surface and Atmosphere**
▸ What Happens to Incoming Solar Radiation?

When radiation strikes an object, there are usually three different results. First, some of the energy is *absorbed* by the object. Recall that when radiant energy is absorbed, the molecules begin to vibrate faster, 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 2-13 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 energy reaching 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 such as snow and water. 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 back to space, or absorbed by the atmosphere? As we shall see, it depends greatly upon the *wavelength* of the energy being transmitted, as well as upon the size and nature of the absorbing or reflecting substance.

Reflection and Scattering

Reflection is the process whereby light bounces back from an object at the same angle at which it encounters a surface and with the same intensity (Figure 2-14a). By contrast,

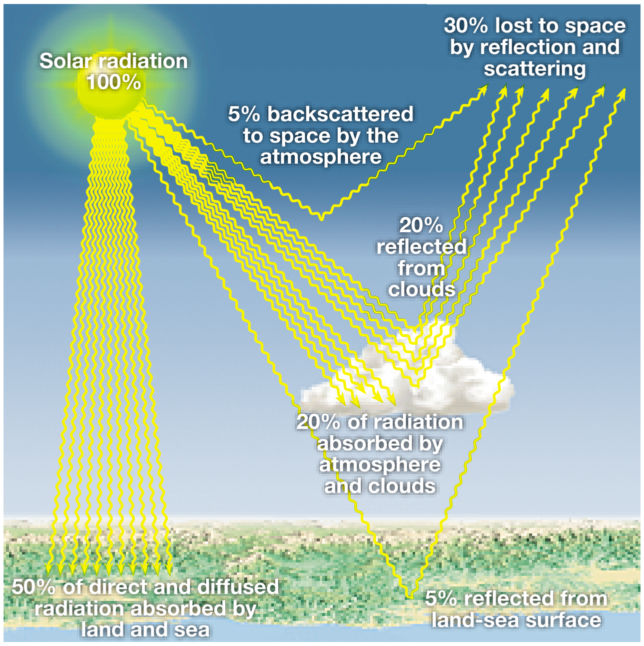


FIGURE 2-13 Average distribution of incoming solar radiation by percentage. More solar energy is absorbed by Earth's surface than by the atmosphere. Consequently, the air is not heated directly by the Sun, but is heated indirectly from Earth's surface.

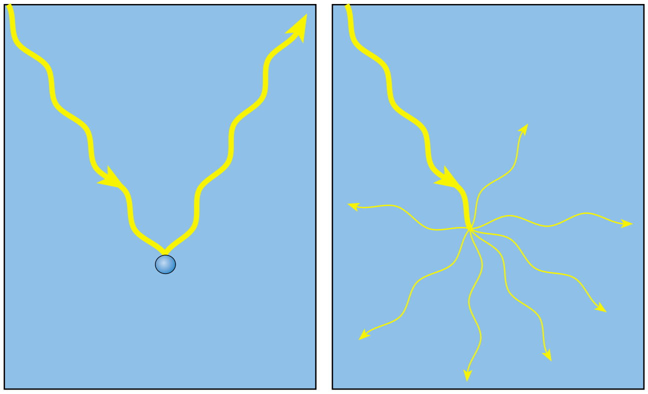
scattering produces a larger number of weaker rays, traveling in different directions. Although scattering disperses light both forward and backward (**backscattering**), more energy is dispersed in the forward direction (Figure 2-14b).

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 reaching the outer atmosphere is reflected back to space (Figure 2-13). 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 radiation that is reflected by a surface is called its **albedo.** The albedo from place to place as well as from time to time varies considerably, depending on the amount of cloud cover and particulate matter in the air, plus the angle of the Sun's rays and the nature of the surface. Figure 2-15 gives the albedo for various surfaces. Fresh snow and thick clouds have high albedos (good reflectors). By contrast, dark soil is not very reflective and thus absorbs much of the radiation it receives. In the case of a lake or the ocean, note that the angle at which the Sun's rays strike the water surface greatly affects its albedo.

The albedo for Earth as a whole (planetary albedo) is 30 percent. The amount of light reflected from Earth's land–sea surface represents only about 5 percent of the total planetary albedo (Figure 2-13). Clouds are largely responsible for most of Earth's "brightness" as seen from space. This high reflectivity of clouds should not surprise anyone who has tried to drive on a foggy night with bright lights.

In comparison to Earth, the Moon, which is without clouds or an atmosphere, has an average albedo of only 7 percent. Even though a full Moon gives us a good bit of light on a clear night, the much brighter Earth would provide an astronaut on the Moon with far more light for an "Earth-lit" walk at night.



(a) Reflection

(b) Scattering

FIGURE 2-14 Reflection and scattering. (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 different directions. Usually more energy is scattered in the forward direction than is backscattered.

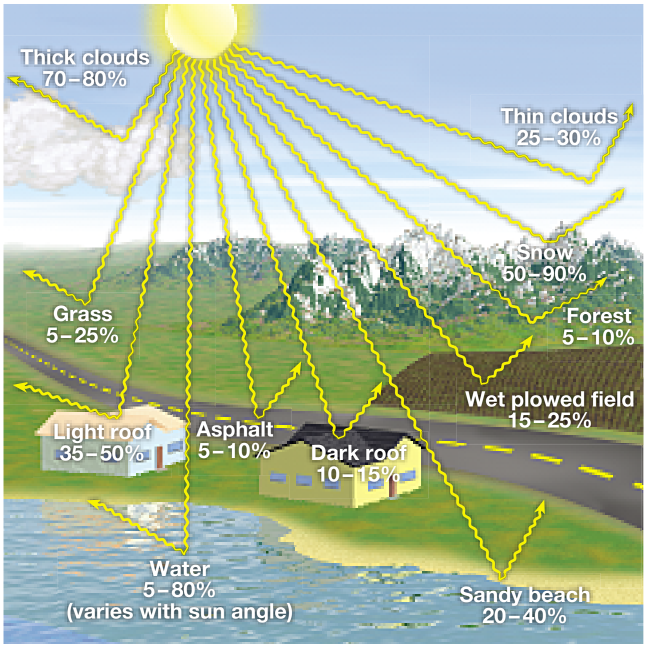


FIGURE 2-15 Albedo (reflectivity) of various surfaces. In general, light-colored surfaces tend to be more reflective than dark-colored surfaces and thus have higher albedos.

Blue Skies and Red Sunsets. 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 like the Moon and Mercury, which are without atmospheres, have dark skies and "pitch-black" shadows, even during daylight hours. Overall, about one-half of solar radiation that is absorbed at Earth's surface arrives as scattered light.

To a large extent, the degree of scattering is determined by the size of the intervening gas molecules and dust particles. When light is scattered by very small particles, primarily gas molecules, it is distributed in all directions; however, more energy is scattered in the forward direction. The light that is lost to space is said to be *backscattered.*

Gas molecules more effectively scatter the shorter wavelengths (blue and violet) of visible light than the longer wavelengths (red and orange). This fact, in turn, explains the blue color of the sky and the orange and red colors seen at sunrise and sunset (Figure 2–16). Remember, sunlight appears white, but it is composed of all colors. When the Sun is overhead, you can look in any direction away from the direct Sun and see predominantly blue light, which is the wavelength more readily scattered by the atmosphere.

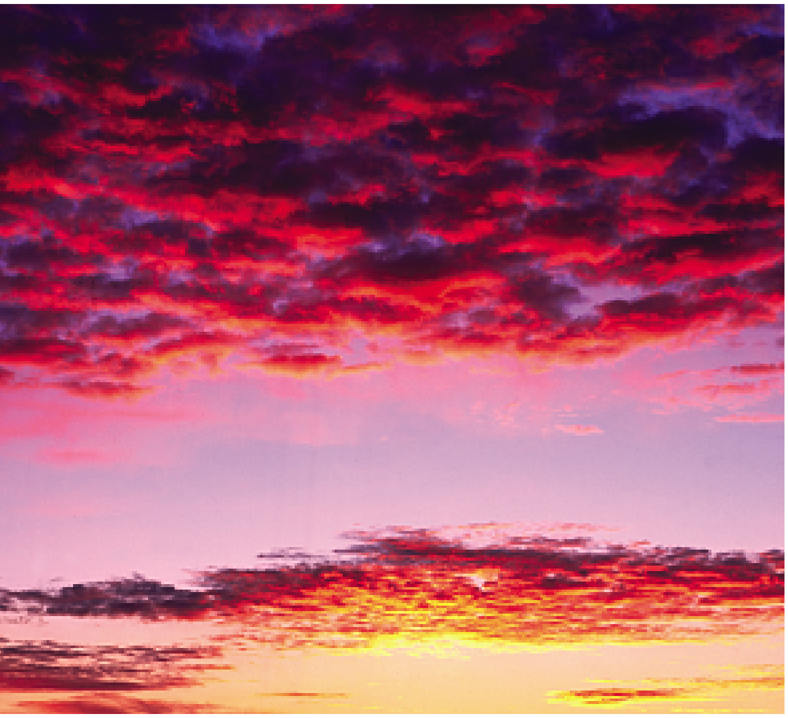
Conversely, the Sun appears to have an orangish-to-reddish tint when viewed near the horizon (Figure 2–17). This is because solar radiation must travel through a greater thickness of atmosphere before it reaches your eyes (see Table 2–1). As a consequence, most of the blue and violet wavelengths will be scattered out, leaving light that consists mostly of reds and oranges. The reddish appearance of clouds during sunrise and sunset also results because the clouds are illuminated by light from which the blue color has been subtracted by scattering.

The most spectacular sunsets occur when large quantities of fine dust or smoke particles penetrate into the stratosphere. For three years after the great eruption of the Indonesian volcano Krakatau in 1883, brilliant sunsets occurred worldwide. The European summer that followed this colossal explosion was cooler than normal, a fact that has been attributed to the greater loss of radiation caused by backscattering.

Large particles associated with haze, fog, or smog scatter light more equally in all wavelengths. Because no color is predominant over any other, the sky appears white or gray on days when large particles are abundant. Scattering of sunlight by haze, water droplets, or dust particles makes it possible for us to observe bands (or rays) of sunlight called *crepuscular rays*. These bright fan-shaped bands are most commonly seen when the Sun shines through a break in the clouds, as shown in Figure 2–18. Crepuscular rays can also be observed around twilight when towering clouds cause alternating lighter and darker bands (light rays and shadows) to streak across the sky.

In summary, the color of the sky gives an indication of the number of large or small particles present. Lots of small particles produce red sunsets, whereas large particles produce a white sky. Furthermore, the bluer the sky, the cleaner the air.

FIGURE 2-16 At sunset, clouds often appear red because they are illuminated by sunlight in which most of the blue light has been lost due to scattering. *(Photo by Carr Clifton/Minden Pictures)*



Absorption by Earth's Surface and Atmosphere

Although Earth's surface is a relatively good absorber (effectively absorbs most wavelengths of solar radiation), the atmosphere is not. This accounts for the fact that 50 percent of the solar radiation that reaches Earth is absorbed by Earth's land–sea surface, whereas only 20 percent of this energy is absorbed directly by the atmosphere (see Figure 2–13). The atmosphere is not as effective an absorber because gases are selective absorbers (and emitters) of radiation. As you will see in the following section, this fact greatly influences how the atmosphere is heated.

Freshly fallen snow is another example of a selective absorber. Anyone who has experienced the blinding reflection of sunlight from snow is aware that fresh snow is a poor absorber of visible light (reflects up to 85 percent). Because of this, the temperature directly above a snow-covered surface is colder than it would otherwise be because much of

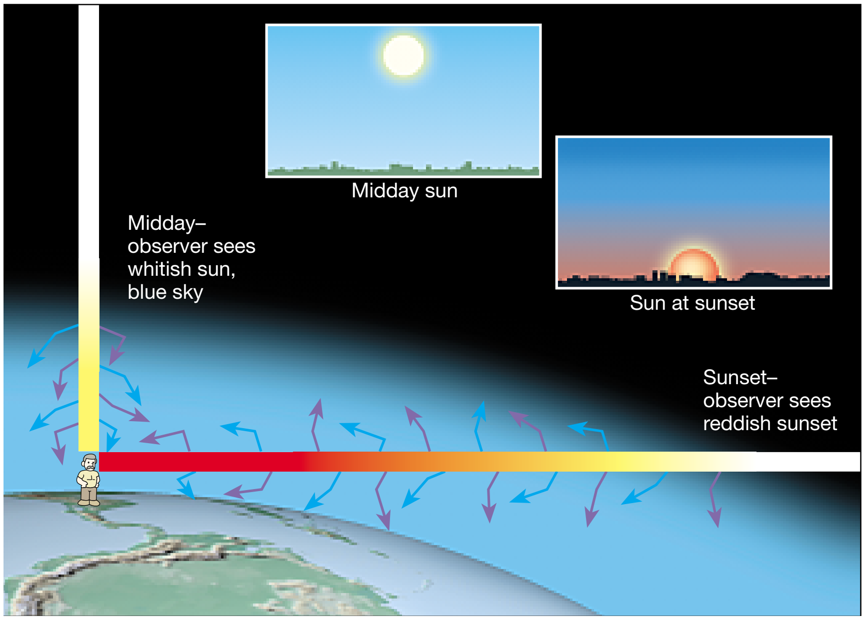


FIGURE 2-17 Short wavelengths (blue and violet) of visible light are scattered more effectively than are longer wavelengths (red, orange). Therefore, when the Sun is overhead, an observer can look in any direction and see predominantly blue light that was selectively scattered by the gases in the atmosphere. By contrast, at sunset, the path that light must take through the atmosphere is much longer. Consequently, most of the blue light is scattered before it reaches an observer. Thus, the Sun appears reddish in color.

the incoming radiation is reflected away. However, snow is a very good absorber (absorbs up to 95 percent) of the infrared (heat) radiation that is emitted from Earth's surface. As the ground radiates heat upward, the lowest layer of snow absorbs this energy and reradiates most of it downward. Thus, the depth at which a winter's frost can penetrate into the ground is much less when the ground has a snow cover than in an equally cold region without snow. The statement "The ground is blanketed with snow" can be taken literally. Farmers who plant winter wheat desire a deep snow cover because it insulates their crops from bitter midwinter temperatures.

FIGURE 2-18 Crepuscular rays are produced when haze scatters light. Crepuscular rays are most commonly seen when the Sun shines through a break in the clouds. *(Photo by Adam Jones/Visuals Unlimited, Inc.)*

Radiation Emitted by Earth

Heating Earth's Surface and Atmosphere

▸ The Greenhouse Effect

Although we often talk about radiation in terms of the Sun, recall that *all* objects continuously emit radiation. Because Earth is much cooler than the Sun, it emits considerably less radiant energy. Furthermore, radiation emanating from Earth's surface and atmosphere is emitted at longer wavelengths than most solar radiation. Over 95 percent of Earth's radiation has wavelengths between 2.5 and 30 micrometers, placing it in the long end of the infrared band of the electromagnetic spectrum (Figure 2–19). Recall that the bulk of solar radiation is emitted in wavelengths shorter than 2.5 micrometers (shortwave radiation). This difference between incoming solar radiation and radiation emitted by Earth is very important to our understanding of how our atmosphere is heated.

Heating the Atmosphere

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, this energy is transformed into internal molecular motion, which is detectable as a rise in temperature. *Thus, it is the gases that are the most effective absorbers of radiation that play the primary role in heating the atmosphere.*

At first glance Figure 2–19 appears complicated; nevertheless, it is a useful aid to understanding how the atmosphere is heated. The upper portion shows that most (95 percent) incoming solar radiation has wavelengths between 0.1 and 2.5 micrometers (abbreviated μm) and includes the

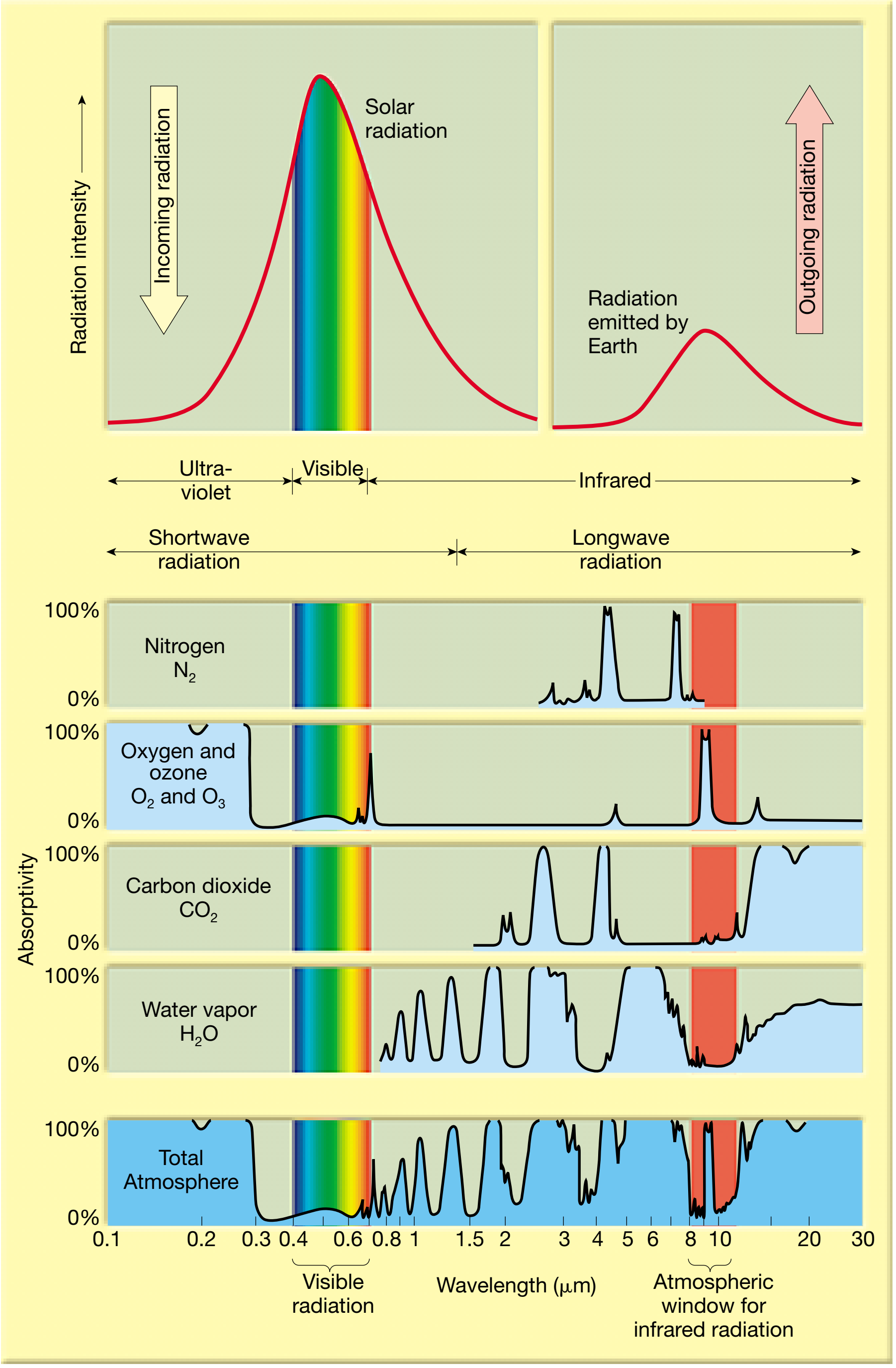


FIGURE 2-19 The absorptivity of selected gases of the atmosphere and the atmosphere as a whole. The atmosphere as a whole is quite transparent to solar radiation between 0.3 and 0.7 micrometer, which includes the band of visible light. Most solar radiation falls in this range, explaining why a large amount of solar radiation penetrates the atmosphere and heats Earth's surface. Also, note that longwave infrared radiation in the zone between 8 and 12 micrometers can escape the atmosphere most readily. This zone is called the atmospheric window. *(Data after R. G. Fleagle and J. A. Businger,* An Introduction to Atmospheric Physics. *1963 by Academic Press)*

band of visible light (shown as the colors of the rainbow). The lower half of Figure 2–19 gives the absorptivity of the principal atmospheric gases. Note that nitrogen, the most abundant constituent in the atmosphere (78 percent), is a relatively poor absorber of incoming solar radiation because it absorbs best in that part of the electromagnetic spectrum, with wavelengths greater than 2.5 micrometers.

The only significant absorbers of incoming solar radiation are water vapor, oxygen, and ozone, which together accounts for most of the solar energy absorbed directly by the atmosphere. Oxygen and ozone are efficient absorbers of high-energy, shortwave radiation. Oxygen removes most of the shorter-wavelength UV radiation high in the atmosphere, and ozone absorbs UV rays in the stratosphere between 10 and 50 kilometers (6 and 30 miles). The absorption of UV energy in the stratosphere accounts for the high temperatures experienced there. More important, without the removal of UV radiation, human life would not be possible because UV energy disrupts the genetic code (see Chapter 1).

Students Sometimes Ask…

What causes leaves on deciduous trees to change color each fall?

The leaves of all deciduous trees contain the pigment chlorophyll, which gives them a green color. The leaves of some trees also contain the pigment carotene, which is yellow, and still others produce a class of pigments that appear red in color. During summer, leaves are factories generating sugar from carbon dioxide and water by the action of light on chlorophyll. As the dominant pigment, chlorophyll causes the leaves of most trees to appear green. The shortening days and cool nights of autumn trigger changes in deciduous trees. With a drop in chlorophyll production, the green color of the leaves fades allowing other pigments to be seen. If the leaves contain carotene, as do birch and hickory, they will change to bright yellow. Other trees, such as red maple and sumac, display the brightest reds and purples in the autumn landscape.

Looking at the bottom of Figure 2–19, you can see that for the atmosphere as a whole, none of the gases are effective absorbers of radiation that has wavelengths between 0.3 and 0.7 micrometers. This region of the spectrum corresponds to the visible light band, which constitutes about 43 percent of the energy radiated by the Sun. Because the atmosphere is a poor absorber of visible radiation, most of this energy is transmitted to Earth's surface. Thus, we say that *the atmosphere is nearly transparent to incoming solar radiation and that direct solar energy is not an effective "heater" of Earth's atmosphere.*

We can also see in Figure 2–19 that the atmosphere as a whole is a relatively efficient absorber of longwave (infrared) radiation emitted by Earth (see bottom right of Figure 2–19). Water vapor and carbon dioxide are the principal absorbing gases, with water vapor absorbing about 60 percent of the radiation emitted by Earth. Therefore, water vapor accounts (more than any other gas) for the warm temperatures of the lower troposphere, where it is most highly concentrated.

Although the atmosphere is an effective absorber of radiation emitted by Earth's surface, it is nevertheless quite transparent to the band of radiation between 8 and 12 micrometers. Notice in Figure 2-19 (lower right) that the gases in the atmosphere absorb very little energy in these wavelengths. Because the atmosphere is transparent to radiation between 8 and 12 micrometers, much like window glass is transparent to visible light, this band is called the **atmospheric window.** Although other "atmospheric windows" exist, the one located between 8 and 12 micrometers is the most significant because this happens to be located where Earth's radiation is most intense.

By contrast, clouds that are composed of tiny liquid droplets are excellent absorbers of this energy. This explains why nighttime temperatures remain higher on cloudy nights than on clear nights. Clouds absorb outgoing radiation and reradiate much of this energy back to Earth's surface. Thus, clouds serve a purpose similar to window blinds because they effectively shut the atmospheric window. As a result, clouds lower the rate at which the surface cools.

Because the atmosphere is largely transparent to solar (shortwave) radiation but more absorptive of the longwave radiation emitted by Earth, the atmosphere is heated from the ground up, instead of vice versa. This explains the general drop in temperature with increased altitude in the troposphere. The farther from the "radiator" (Earth's surface), the colder it gets. On average, the temperature drops 6.5°C for each kilometer increase in altitude, a figure known as the *normal lapse rate.* The fact that the atmosphere does not acquire the bulk of its energy directly from the Sun, but is heated by Earth's surface, is of utmost importance to the dynamics of the weather machine.

The Greenhouse Effect

If Earth had no atmosphere, it would experience an average surface temperature far below freezing. But the atmosphere warms the planet and makes Earth livable. The extremely important role the atmosphere plays in heating Earth's surface has been named the **greenhouse effect.**

As you saw earlier, cloudless air is largely transparent to incoming shortwave solar radiation and, hence, transmits it to Earth's surface. By contrast, a significant fraction of the longwave radiation emitted by Earth's land–sea surface is absorbed by water vapor, carbon dioxide, and other trace gases in the atmosphere. This energy heats the air and increases the rate at which it radiates energy, both out to space and back toward Earth's surface. The energy that is emitted back to the surface causes it to heat up more, which then results in greater emissions from the surface. This complicated game of "pass the hot potato" keeps Earth's average temperature 33°C (59°F) warmer than it would otherwise be (Figure 2–20). Without these absorptive gases in our atmosphere, Earth would not provide a suitable habitat for humans and other life forms.

This natural phenomenon was named the greenhouse effect because it was once thought that greenhouses were heated in a similar manner. The glass in a greenhouse allows shortwave solar radiation to enter and be 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. It has been shown, however, that air inside greenhouses attains higher temperatures than outside air mainly because greenhouses restrict the exchange of air between the inside and outside. Nevertheless, the term "greenhouse effect" remains.

The popular press frequently points to the greenhouse effect as the "villain" of the global warming problem. It is important to note that the greenhouse effect and global warming *are not* the same thing. Without the greenhouse

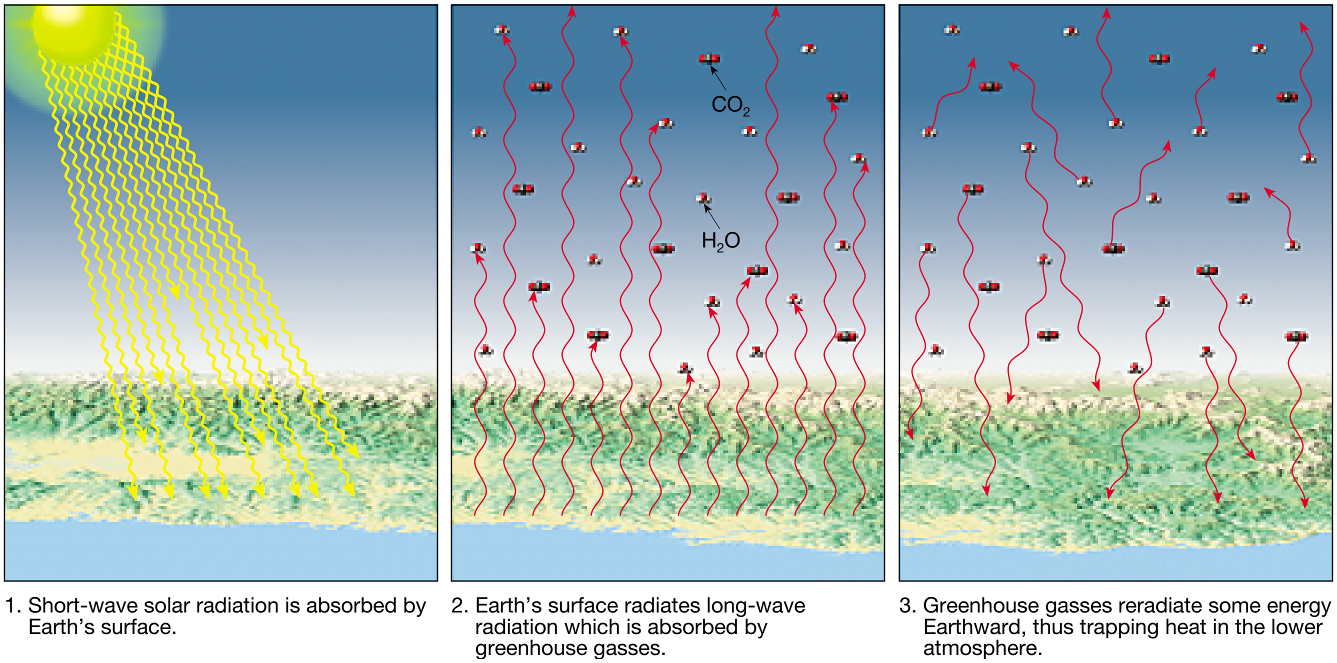


FIGURE 2-20 The heating of the atmosphere. Most of the short-wavelength radiation from the Sun passes through the atmosphere and is absorbed by Earth's land–sea surface. This energy is then emitted from the surface as longer-wavelength radiation, much of which is absorbed by certain gases in the atmosphere. Some of the energy absorbed by the atmosphere will be reradiated Earthward. This so-called greenhouse effect is responsible for keeping Earth's surface much warmer than it would be otherwise.

effect Earth would be uninhabitable. We do have mounting evidence that human activity (particularly the release of carbon dioxide into the atmosphere) is responsible for a rise in global temperature (see Chapter 14). Thus, human activity seems to be enhancing an otherwise natural process (the greenhouse effect) to increase Earth's temperature. Nevertheless, it is wrong to equate the greenhouse phenomenon, which makes life possible, with undesirable changes to our atmosphere caused by human activities.

Students Sometimes Ask…

Is Venus so much hotter than Earth because it is closer to the Sun?

Proximity to the Sun is actually not the primary factor. On Earth, water vapor and carbon dioxide are the primary greenhouse gases and are responsible for elevating Earth's average surface temperature by 33°C (59°F). However, greenhouse gases make up less than 1 percent of Earth's atmosphere. By contrast, the Venusian atmosphere is much denser and consists of 97 percent carbon dioxide. Thus, the Venusian atmosphere experiences extraordinary greenhouse warming, which is estimated to raise its surface temperature by 523°C (941°F).

Role of Clouds in Heating Earth

Clouds, like water vapor and carbon dioxide, are good absorbers of infrared radiation emitted by Earth (see Box 2–5). Thus, at night clouds play a key role in keeping the surface warm. A thick cloud cover will absorb most outward directed radiation and radiate much of that energy back to the surface. This explains why on clear, dry nights the surface cools considerably more than on cloudy or humid evenings. Furthermore, although desert areas often experience high daytime temperatures, they are also likely to experience cold nights, for they generally have cloudless skies.

During daylight hours the effect of clouds on heating Earth's surface depends on the type of clouds present. High, thin clouds primarily transmit incoming solar radiation. At the same time these clouds absorb a portion of the outgoing infrared radiation emitted by Earth and radiate some of that energy back to the surface. The net effect is that high thin clouds tend to warm the surface.

The impact of low, thick clouds is opposite that of high clouds. Thick, low clouds have a high albedo and therefore reflect a significant portion of incoming solar radiation back to space. Because less solar radiation is transmitted, Earth's surface is cooler than it would otherwise be.

Whether a given cloud will cause the surface temperature to be higher or lower than when the sky is clear depends on several factors, including the time of day, the cloud's thickness, its height, and the nature of the particles that compose it. The balance between the cooling and warming effects of

BOX 2-5 Infrared Imaging

It is worth noting that our eyes have evolved to be sensitive to the wavelengths of solar radiation having the greatest intensities (visible radiation). If early humans had been solely dependent upon hunting nocturnal mammals (warm-blooded), evolutionary changes might have resulted in "eyes" sensitive to infrared radiation (heat), just like those of some reptiles. Despite our inability to naturally see infrared energy, we have developed artificial detectors (including infrared film) capable of extending our vision into the long-wavelength part of the electromagnetic spectrum.

One type of infrared imaging employs satellites to detect infrared radiation emitted by Earth's surface and atmosphere. From these images the temperatures of objects emitting radiation, such as clouds, large bodies of water, and various landforms, can be established. Recall that the wavelengths of radiation emitted by an object are temperature-dependent. When more of the energy is emitted in shorter wavelengths, it translates to objects at higher temperatures, whereas longer wavelengths indicate surfaces at lower temperatures.

One technique uses infrared images to determine which clouds are the most probable precipitation producers. The high tops of towering thunderstorms are colder than the tops of clouds at lower altitudes (less vertically developed clouds). In the image shown in Figure 2–E the highest (coldest) cloud tops are associated with towering storm clouds that are part of Hurricane Isidore in the Gulf of Mexico. The tallest clouds and thus the heaviest rain are in the areas shaded in red and yellow.

Unlike photos produced by exposing film to visible light, infrared images can be made at any time of the day or night. The military uses infrared imaging in their "night vision" technology to detect such things as troop movements made under the cover of darkness.

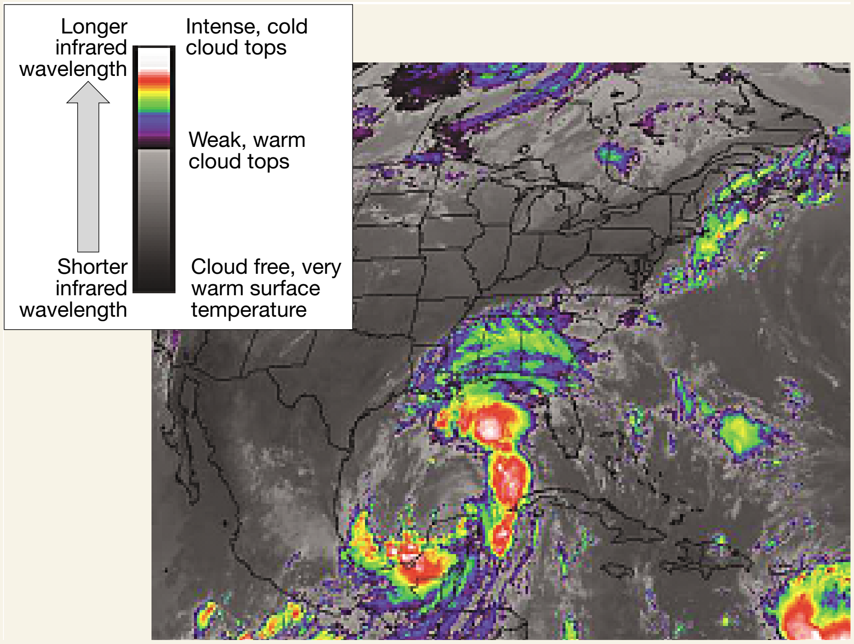


FIGURE 2-E This infrared image shows the tops of the towering storm clouds (red and yellow) that were part of Hurricane Isidore as it crossed the Gulf of Mexico in late September 2002. *(Image courtesy of NASA)*

clouds is quite close; however, averaging the influence of all the clouds around the globe, cooling predominates.

Heat Budget

Worldwide, Earth's average temperature remains relatively constant, despite seasonal cold spells and heat waves. This stability indicates that a balance exists between the amount of incoming solar radiation and the amount of radiation emitted back to space; otherwise, Earth would be getting progressively colder or progressively warmer. The annual balance of incoming and outgoing radiation is called Earth's **heat budget.** The following examination of this budget provides a good review of the process just discussed.

Figure 2–21 illustrates Earth's heat budget. For simplicity we will use 100 units to represent the solar radiation intercepted at the outer edge of the atmosphere. You have

BOX 2-6 Solar Power

Nearly 95 percent of the world's energy needs are derived from fossil fuels, primarily oil, coal, and natural gas. Present estimates indicate that the amount of recoverable fossil fuels may equal 10 trillion barrels of oil, which at the present rate of consumption is enough to last 170 years. Of course, as world population increases, the rate of consumption will climb. Thus, reserves will eventually be in short supply. In the meantime, the adverse environmental impacts associated with burning huge quantities of fossil fuels will likely grow more severe. How can a growing demand for energy be met without radically altering the planet we inhabit? Although no clear answer has yet emerged, we must consider greater use of alternate energy sources, such as solar power.

The term *solar energy* generally refers to the direct use of the Sun's rays to supply energy for the needs of people. The simplest, and perhaps most widely used, *passive solar collectors* are south-facing windows. As shortwave sunlight passes through the glass, its energy is absorbed by objects in the room. These objects, in turn, radiate longwave heat that warms the air in the room. In the United States we often use south-facing windows, along with better insulated and more airtight construction, to reduce heating costs substantially.

More elaborate systems used for home heating involve an *active solar collector.* These roof-mounted devices are normally large blackened boxes that are covered with glass. The heat they collect can be transferred to where it is needed by circulating air or fluids through pipes. Solar collectors are also used successfully to heat water for domestic and commercial needs. In Israel, for example, about 80 percent of all homes are equipped with solar collectors that provide hot water.

Although solar energy is free, the necessary equipment and its installation are not. The initial cost of setting up a system, including a supplemental heating unit for times when solar energy is diminished (cloudy days and winter) or unavailable (nighttime),

FIGURE 2-F Solar One, a solar installation used to generate electricity in the Mojave Desert near Barstow, California. *(Photo by Thomas Braise/Corbis/Stock Market)*

already seen that, of the total radiation that reaches Earth, roughly 30 units (30 percent) are reflected back to space. The remaining 70 units are absorbed, 20 units within the atmosphere and 50 units by Earth's land–sea surface. How does Earth transfer this energy back to space?

If all of the energy absorbed by our atmosphere, land, and water were reradiated directly and immediately back to space, Earth's heat budget would be simple—100 units of radiation received and 100 units returned to space. In fact, this does happen *over time* (minus small quantities of energy that become locked up in biomass that may eventually become fossil fuel). What makes the heat budget complicated is the behavior of certain greenhouse gases, particularly water vapor and carbon dioxide. As you learned, these greenhouse gases absorb a large share of outward-directed infrared radiation and radiate much of that energy back to Earth. This "recycled" energy significantly increases the radiation received by Earth's surface. In addition to the 50 units received directly from the Sun, Earth's surface receives another 94 units from the atmosphere, bringing the total absorbed to 144 units. A balance is maintained, however, because all 144 units are returned to the atmosphere and eventually lost to space.

Earth's surface loses the 144 units mainly by emitting longwave radiation skyward. As Figure 2–21 illustrates, 102 units are emitted from Earth's surface and absorbed by the

FIGURE 2-G A proposed solar facility near Los Angeles will consist of a 20,000-dish array using Stirling dish technology. *(Photo by Randy J. Montoya/ Sandia National Laboratories)*

can be substantial. Nevertheless, over the long term, solar energy is economical in most parts of the United States and will become even more cost-efficient as the price of other fuels increases.

Research is currently underway to improve the technologies for concentrating sunlight. One method being examined uses mirrors that track the Sun and keep its rays focused on a receiving tower. A facility, with an array of 2000 mirrors, has been constructed near Barstow, California (Figure 2-F). Solar energy focused on the tower heats water in pressurized panels to over 500°C. The superheated water is then transferred to turbines, which turn electrical generators.

Another type of collector uses photovoltaic (solar) cells that convert the Sun's energy directly into electricity. A large experimental facility using photovoltaic cells is located near Hesperia, California, and supplies electricity to customers of Southern California Edison.

In late 2005, Southern California Edison announced an agreement that could result in construction of a massive 4,500-acre solar-generating facility located 70 miles northeast of Los Angeles. The technology being employed, called the *Stirling dish,* converts thermal energy to electricity by using a mirror array to focus the Sun's rays on the receiver end of a Stirling engine (Figure 2-G). The internal side of a receiver then heats hydrogen gas, causing it to expand. The pressure created by the expanding gas drives a piston, which turns a small electric generator. When completed, this facility is expected to consist of a 20,000-dish array that will produce 500 megawatts of electricity, enough to serve 278,000 homes.

atmosphere. In addition, 12 units are transmitted through the atmosphere without being absorbed. (Recall that radiation between 8 and 12 micrometers escapes the troposphere most readily because water vapor and carbon dioxide do not absorb these wavelengths.) In addition, energy is carried from Earth's land–sea surface to the atmosphere by water molecules during the process of evaporation (23 units) and by conduction and convection (7 units).

The energy transferred to the atmosphere is reradiated skyward as well as toward the surface. However, a balance has been established, so that on average the atmosphere radiates back to space the same amount of energy as it receives. A careful examination of Figure 2–21 confirms that incoming shortwave radiation is in fact balanced by outgoing longwave radiation.

Latitudinal Heat Balance

Because the amount of incoming solar radiation is nearly equal to the amount of outgoing radiation for Earth as a whole, the average worldwide temperature remains constant. However, the balance of incoming and outgoing radiation that holds for the entire planet obviously is not maintained at each latitude. Averaged over the entire year, a zone around Earth between 38°N and 38°S *receives more solar radiation than is lost to space* (Figure 2–22). Not surprisingly, this zone,

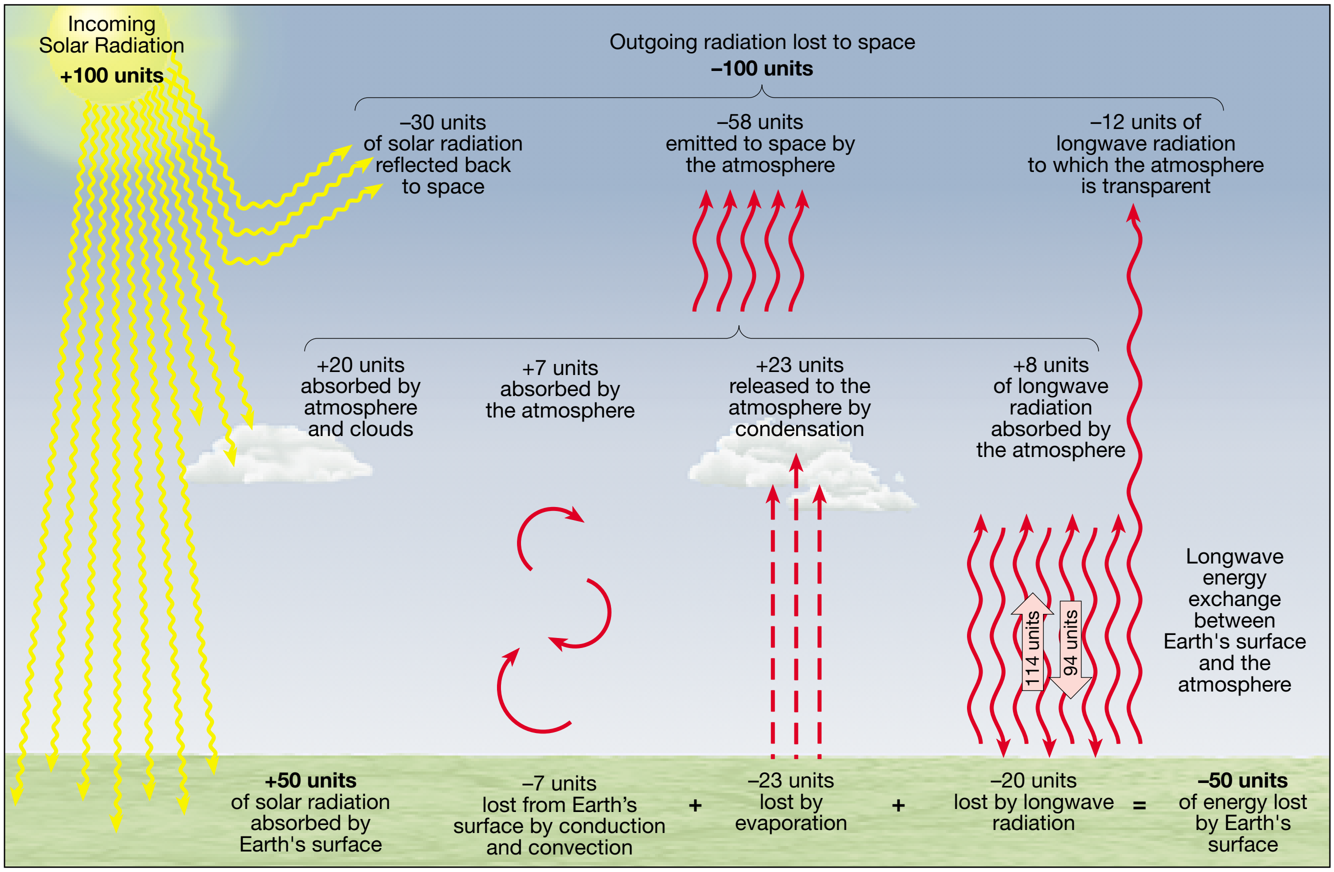


FIGURE 2-21 Heat budget of Earth and atmosphere. These estimates of the average global energy budget come from satellite observations and radiation studies. As more data are accumulated these numbers will be modified. *(Data from Kiehl, Trenberth, Liou, and others.)*

centered on the equator, includes the southern United States and the warm tropical areas of Earth. The opposite is true for higher latitudes, where *more heat is lost through longwave terrestrial radiation than is received.*

A conclusion that might be drawn is that the tropics should be getting hotter and the poles should be getting colder. But we know that is not happening. Instead, the atmosphere and the oceans act as giant thermal engines transferring surplus heat from the tropics poleward. In effect, it is this energy imbalance that drives the winds and the ocean currents.

The amount of solar radiation received at a given location fluctuates with changes in cloud cover and atmos-

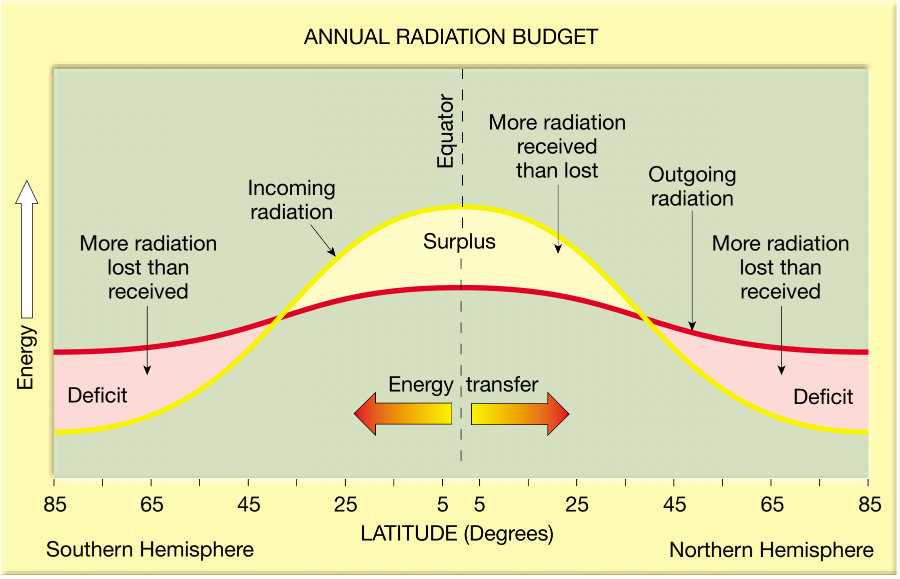


FIGURE 2-22 Latitudinal heat balance averaged over the entire year. We see that in a zone extending 38 degrees on both sides of the equator, the amount of incoming solar radiation exceeds the loss from outgoing Earth radiation. The reverse is true for the middle and high (polar) latitudes, where losses from outgoing Earth radiation exceed gains from incoming solar radiation.

pheric composition. For example, the tropics often experience thick cloud cover, which reduces incoming radiation. Events such as forest fires, dust storms, and volcanic eruptions can also reduce the amount of incoming solar radiation. More important, however, are seasonal changes in Sun angle and length of daylight, which determine, to a large degree, the amount of radiation reaching the ground at any given latitude.

Notice in December (Figure 2-23) that the zone of maximum heating is centered roughly over the Tropic of Capricorn, because this is the latitude that experiences the direct rays of the Sun. By contrast, short days and low

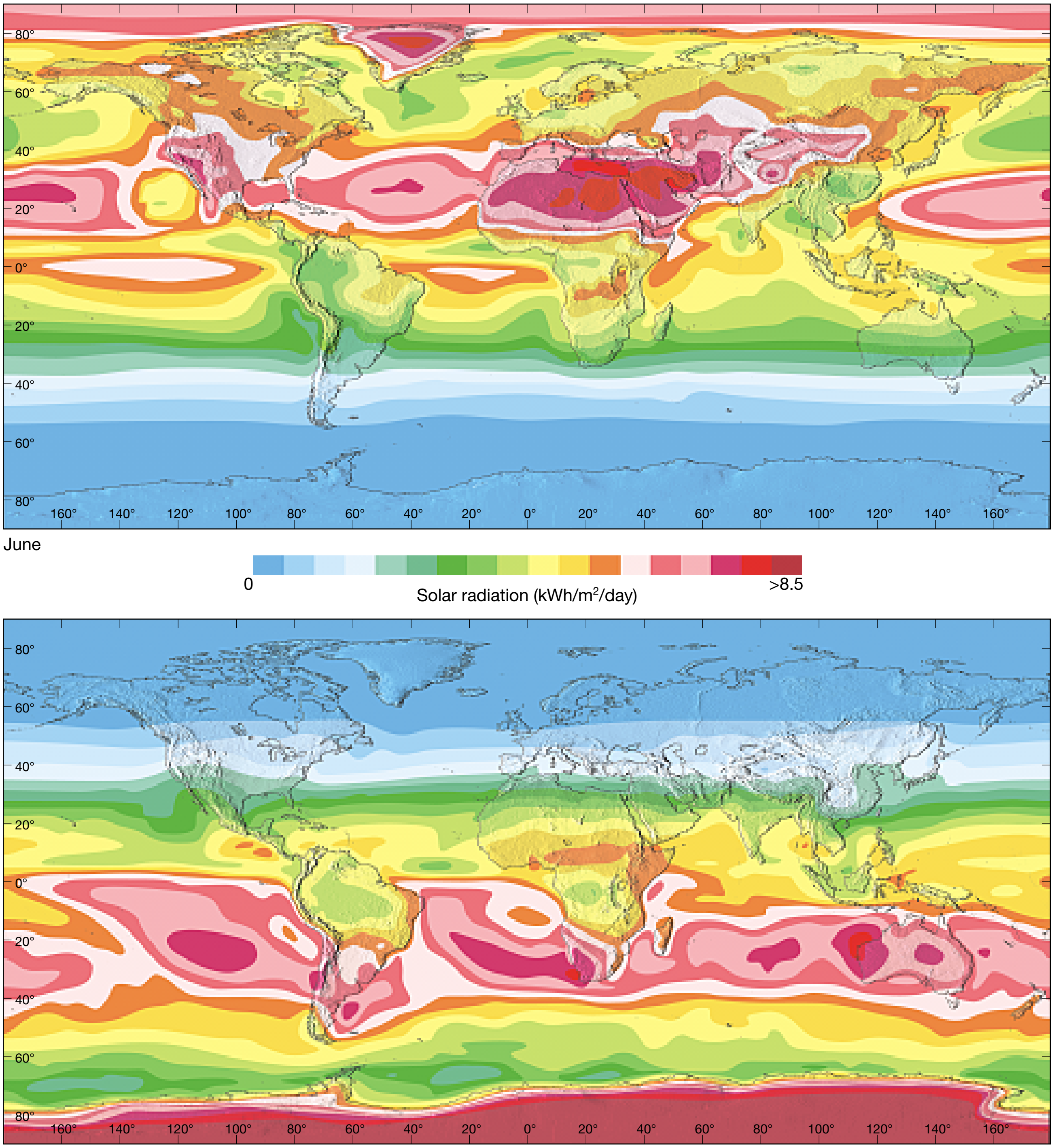


FIGURE 2-23 These false-color images show the average rate of incoming solar radiation at Earth's surface for the months of June and December. The colors correspond to values (kilowatt hours per square meter per day) measured by a variety of Earth-observing satellites and averaged over a 10-year period. Because the measurements are taken at Earth's surface, cloud cover reduces the radiation reaching the ground. This effect is apparent in some tropical regions where cloud cover is extensive.

Sun angles are mainly responsible for the relatively small amounts of solar radiation reaching the middle and high latitudes in the Northern Hemisphere. Also notice that Antarctica receives what might appear to be an unusually large amount of solar radiation in December. This occurs because in December much of Antarctica experiences nearly continuous daylight. Despite the abundance of energy received during the Antarctic summer, it is not enough to balance the outflows that occur during the long winter. Moreover, much of the summer sunshine in Antarctica is reflected back to space by its snow-and ice-covered surface. The top part of Figure 2-23 shows the opposite situation, summer in the Northern Hemisphere. In June the incoming solar radiation is most intense near the Tropic of Cancer, and the Northern Hemisphere is bathed in sunshine.

The shift in incoming solar radiation from the Southern to Northern Hemisphere and back again can be clearly seen by comparing the June and December maps in Figure 2-22. Because energy imbalances drive Earth's general circulation, the regions of greatest energy transfer also migrate seasonally.

It should be of interest to those who live in the middle latitudes—in the Northern Hemisphere, from the latitude of New Orleans at 30°N to the latitude of Winnipeg, Manitoba, at 50°N—that most heat transfer takes place across this region. Consequently, much of the stormy weather experienced in the middle latitudes can be attributed to this unending transfer of heat from the tropics toward the poles. These processes are discussed in more detail in later chapters.

Chapter Summary

- Earth has two principal motions—*rotation* and *revolution*. Rotation is the spinning of Earth about its axis. Revolution refers to the movement of Earth in its orbit around the Sun.
- The two most important reasons for the variation in solar energy reaching a particular location are the seasonal changes in the angle at which the Sun's rays strike the surface and the length of daylight. The seasonal variation in the angle of the Sun affects where on Earth the solar rays are most concerned and the thickness of atmosphere the rays must penetrate.
- The four days each year given special significance based on the annual migration of the direct rays of the Sun and its importance to the yearly cycle of weather are (1) June 21/22, the *summer solstice* in the Northern Hemisphere, when the vertical rays of the Sun are striking 23 1/2° north latitude (*Tropic of Cancer*), (2) December 21/22, the *winter solstice* in the Northern Hemisphere, when the vertical rays of the Sun are striking 23 1/2° south latitude (*Tropic of Capricorn*), (3) September 22/23, the *autumnal equinox* in the Northern Hemisphere, when the vertical rays of the Sun strike the equator, and (4) March 21/22, the *spring*, or *vernal, equinox* in the Northern Hemisphere, when the vertical rays of the Sun also strike the equator.
- *Energy* is the ability to do work. The two major categories of energy are (1) *kinetic energy,* which can be thought of as energy of motion, and (2) *potential energy,* energy that has the capability to do work.
- *Heat* is the transfer of energy into or out of an object because of temperature differences between that object and its surroundings.
- The three mechanisms of energy transfer are (1) *conduction,* the transfer of heat through matter by molecular activity, (2) *convection,* the transfer of heat by mass movement or circulation within a substance, and (3) *radiation,* the transfer mechanism by which solar energy reaches our planet.
- *Radiation* or *electromagnetic radiation,* whether X rays, visible light, heat waves, or radio waves, travels as various size waves through the vacuum of space at 300,000 kilometers per second. Shorter wavelengths of radiation are associated with greater energy. The wavelength of visible light ranges from 0.4 micrometer (violet) to 0.7 micrometer (red). Although the Sun emits many forms of radiation, most of the energy is concentrated in the visible and near visible (infrared and ultraviolet) parts of the spectrum. The basic laws of radiation are (1) all objects emit radiant energy, (2) hotter objects radiate more total energy per unit area than colder objects, (3) the hotter the radiating body, the shorter is the wavelength of maximum radiation, and (4) objects that are good absorbers of radiation are also good emitters.
- Approximately 50 percent of the solar energy that strikes the top of the atmosphere reaches Earth's surface. About 30 percent is reflected back to space. The remaining 20 percent of the energy is absorbed by clouds and the atmosphere's gases. The wavelength of the energy being transmitted, as well as the size and nature of the absorbing or reflecting substance, determine whether solar radiation will be scattered, reflected back to space, or absorbed. The fraction of radiation reflected by a surface is called its *albedo.*
- Radiant energy that is absorbed heats Earth and eventually is reradiated skyward. Because Earth has a much lower surface temperature than the Sun, its radiation is in the form of longwave infrared radiation. Because the atmospheric gases, primarily water vapor and carbon diox-

ide, are more efficient absorbers of terrestrial (longwave) radiation, the atmosphere is heated from the ground up. The general drop in temperature with increased altitude in the troposphere (about 6.5°C/kilometer, a figure called the *normal lapse rate*) supports the fact that the atmosphere is heated from below. The transmission of shortwave solar radiation by the atmosphere, coupled with the selective absorption of Earth radiation by atmospheric gases that results in the warming of the atmosphere, is referred to as the *greenhouse effect.*

- Because of the annual balance that exists between incoming and outgoing radiation, called the *heat budget,* Earth's average temperature remains relatively constant despite seasonal cold spells and heat waves.
- Although the balance of incoming and outgoing radiation holds for the entire planet, it is not maintained at each latitude. Averaged over the entire year, a zone around Earth between 38°N and 38°S receives more solar radiation than is lost to space. The opposite is true for higher latitudes, where more heat is lost through outgoing longwave radiation than is received. It is this energy imbalance between the low and high latitudes that drives the global winds and ocean currents, which in turn transfer surplus heat from the tropics poleward. Furthermore, the radiation balance of a given place fluctuates with changes in cloud cover, atmospheric composition, and most important, Sun angle and length of daylight. Thus, areas of radiation surplus and deficit migrate seasonally as the Sun angle and length of daylight change.

Vocabulary Review

advection (p. 42)
albedo (p. 47)
aphelion (p. 33)
atmospheric window (p. 51)
autumnal equinox (p. 35)
backscattered (p. 47)
blackbody (p. 45)
circle of illumination (p. 35)
conduction (p. 42)
convection (p. 42)
diffused light (p. 48)
energy (p. 40)
greenhouse effect (p. 51)
heat (p. 41)
heat budget (p. 53)
inclination of the axis (p. 34)
infrared radiation (p. 43)
kinetic energy (p. 40)
longwave radiation (p. 45)
perihelion (p. 33)
plane of the ecliptic (p. 34)
potential energy (p. 41)
radiation or electromagnetic radiation (p. 43)
reflection (p. 46)
revolution (p. 32)
rotation (p. 32)
scattering (p. 47)
shortwave radiation (p. 45)
spring equinox (p. 35)
summer solstice (p. 35)
temperature (p. 41)
thermal (p. 42)
Tropic of Cancer (p. 35)
Tropic of Capricorn (p. 35)
ultraviolet radiation (p. 43)
visible light (p. 43)
wavelength (p. 43)
winter solstice (p. 35)

Review Questions

1. Can the annual variations in Earth–Sun distance adequately account for seasonal temperature changes? Explain.
2. Why does the amount of solar energy received at Earth's surface change when the angle of the Sun changes?
3. List four characteristics of the summer solstice for the Northern Hemisphere. For the Southern Hemisphere.
4. What is meant by temperature? Heat?
5. Describe the three basic mechanisms of energy transfer. Which mechanism is least important meteorologically?
6. What is the difference between convection and advection?
7. Compare visible, infrared, and ultraviolet radiation. For each, indicate whether it is considered short wavelength or long wavelength.
8. In what part of the electromagnetic spectrum does solar radiation have the highest intensity?
9. Describe the relationship between the temperature of a radiating body and the wavelengths it emits.
10. Why does the daytime sky usually appear blue?
11. Why may the sky appear to have a red or orange tint near sunrise or sunset?
12. What factors influence albedo from time to time and from place to place?
13. Explain why the atmosphere is heated chiefly by radiation from Earth's surface rather than by direct solar radiation.
14. Which gases are the primary heat absorbers in the lower atmosphere? Which one is most influential in weather?
15. How does Earth's atmosphere act as a "greenhouse"?

16. What is responsible for absorbing the largest portion of incoming solar radiation?
17. What is the atmospheric window? How is it "closed"?
18. What two phenomena are driven by the imbalance of heating that exists between the tropics and poles?

Problems

1. Refer to Figure 2–6 and calculate the noon Sun angle on June 21 and December 21 at 50° north latitude, 0° latitude (the equator), and 20° south latitude. Which of these latitudes has the greatest variation in noon Sun angle between summer and winter?
2. For the latitudes listed in Problem 1, determine the length of daylight and darkness on June 21 and December 21 (refer to Table 2–2). Which of these latitudes has the largest seasonal variation in length of daylight? Which latitude has the smallest variation?
3. How would our seasons be affected if Earth's axis were not inclined 23 1/2° to the plane of its orbit but were instead perpendicular?
4. 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?
5. Calculate the noon Sun angle at your location for the equinoxes and solstices.
6. Calculate the noon Sun angle for a city located at 52°N latitude on August 5. What about the same location on January 17? (*Hint:* See Box 2-2.)
7. If Earth had no atmosphere, its longwave radiation emission would be lost quickly to space, making the planet approximately 33 K cooler. Calculate the rate of radiation emitted (E), and the wavelength of maximum radiation emission (λ_{max}) for Earth at 255 K.
8. The intensity of solar radiation can be calculated using trigonometry, as shown in Figure 2-24. For simplicity, consider a solar beam of 1 unit width. The surface area over which the beam would be spread changes with Sun angle, such that

$$\text{Surface area} = \frac{1\text{ unit}}{\sin\ (\text{Sun angle})}$$

Therefore, if the Sun angle at solar noon is 56°:

$$\text{Surface area} = \frac{1\text{ unit}}{\sin 56^\circ} = \frac{1\text{ unit}}{0.829} = 1.206\text{ units}$$

Using this method and your answers to Problem 5, calculate the intensity of solar radiation (surface area) for your location at noon during the summer and winter solstices.

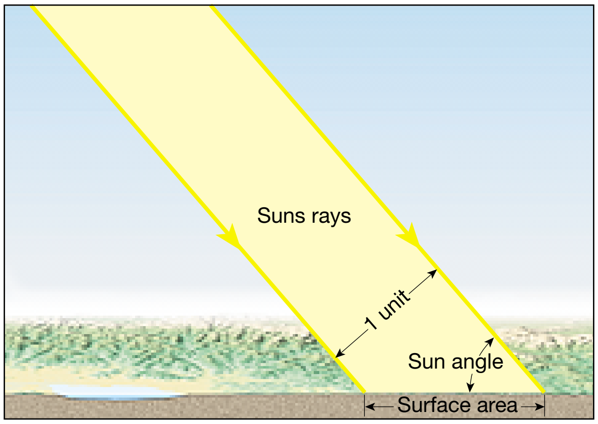


FIGURE 2-24 Calculating solar intensity.

Atmospheric Science Online

The Atmosphere 10e web site uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by meteorology instructors, this site will help improve your understanding of meteorology. Visit **http://www.prenhall.com/lutgens** and click on the cover of *The Atmosphere 10e* to find:

- **Online review quizzes**
- **Critical thinking exercises**
- **Links to chapter-specific web resources**
- **Internet-wide key term searches**

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