● **FIGURE 3.14**
The plane of the ecliptic is defined by the orbit of Earth around the sun. The 23½° inclination of Earth's rotational axis causes the plane of the equator to cut across the plane of the ecliptic.
How many degrees is Earth's axis tilted from the vertical?

Sun Angle, Duration, and Insolation

Understanding Earth's relationships with the sun leads us directly into a discussion of how the intensity of the sun's rays varies from place to place throughout the year and into an examination of the seasonal changes on Earth. Solar radiation received by the Earth system, known as **insolation** (for *in*coming *sol*ar radi*ation*), is the main source of energy on our planet. The seasonal variations in temperature that we experience are due primarily to fluctuations in insolation.

What causes these variations in insolation and brings about seasonal changes? It is true that Earth's atmosphere affects the amount of insolation received. Heavy cloud cover, for instance, will keep more solar radiation from reaching Earth's surface than will a clear sky. However, cloud cover is irregular and unpredictable, and it affects total insolation to only a minor degree over long periods of time.

The real answer to the question of what causes variations in insolation lies with two major phenomena that vary regularly for a given position on Earth as our planet rotates on its axis and revolves around the sun: the duration of daylight and the angle of the solar rays. The amount of daylight controls the duration of solar radiation, and the angle of the sun's rays directly affects the intensity of the solar radiation received. Together, the intensity and the duration of radiation are the major factors that affect the amount of insolation available at any location on Earth's surface.

Therefore, a location on Earth will receive more insolation if (1) the sun shines more directly, (2) the sun shines longer, or (3) both. The intensity of solar radiation received at any

one time varies from place to place because Earth presents a spherical surface to insolation. Therefore, only one line of latitude on the Earth's rotating surface can receive radiation at right angles, while the rest receive varying oblique (sharp) angles (● Fig. 3.15a). As we can see from Figure 3.15b and c, solar energy that strikes Earth at a nearly vertical angle renders more intense energy but covers less area than an equal amount striking Earth at an oblique angle.

The intensity of insolation received at any given latitude can be found using *Lambert's Law,* named for Johann Lambert, an 18th-century German scientist. Lambert developed a formula by which the intensity of insolation can be calculated using the sun's zenith angle (that is, the sun angle deviating from 90° directly overhead). Using Lambert's Law, one can identify, based on latitude, where greater or lesser solar radiation is received on Earth's surface. ● Figure 3.16 shows the intensity of total solar energy received at various latitudes, when the most direct radiation (from 90° angle rays) strikes directly on the equator.

In addition, the atmospheric gases act to diminish, to some extent, the amount of insolation that reaches Earth's surface. Because oblique rays must pass through a greater distance of atmosphere than vertical rays, more insolation will be lost in the process. In 1854, German scientist and mathematician August Beer established a relationship to calculate the amount of solar energy lost as it comes through our atmospheric gases. *Beer's Law,* as it's called, is strongly affected by the thickness of the atmosphere through which the energy must pass.

Since no insolation is received at night, the duration of solar energy is related to the length of daylight received at a particular point on Earth (Table 3.2). Obviously, the longer the period of daylight, the greater the amount of solar radiation that will be received at that location. As we will see in our next section, periods of daylight vary in length through the seasons of the year, as well as from place to place, on Earth's surface.
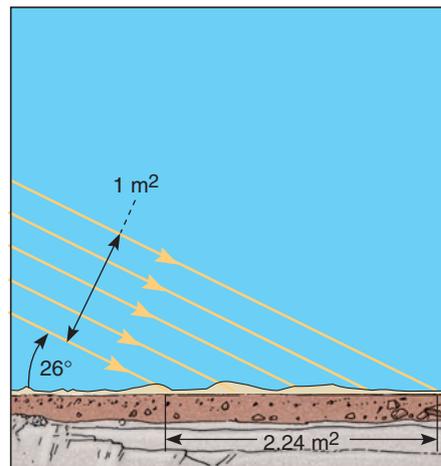
The Seasons

Many people assume that the seasons must be caused by the changing distance between Earth and the sun during Earth's yearly revolution. As noted earlier, the change in this distance is very small. Further, for people in the Northern Hemisphere, Earth is actually closest to the sun in January and farthest away in July (see again Fig. 3.13). This is exactly opposite of that hemisphere's seasonal variations. As we will see, seasons are caused by the 23½° tilt of Earth's equator to the plane of the ecliptic (see again Fig. 3.14) and the parallelism of the axis that is maintained as Earth orbits the sun. About June 21, Earth is in a position in its orbit so that the northern tip of its axis is inclined toward the sun at an angle of 23½°. In other words, the plane of the ecliptic (the 90° sun angle) is directly on 23½° N latitude. This day during Earth's orbit is called the summer **solstice** (from Latin: *sol,* sun; *sistere,* to stand) in the Northern Hemisphere. We can best see what is happening if we refer to ● Figure 3.17, position A. In that diagram, we can see that the Northern and Southern Hemispheres receive unequal amounts of light from the sun. That is, as we imagine rotating Earth
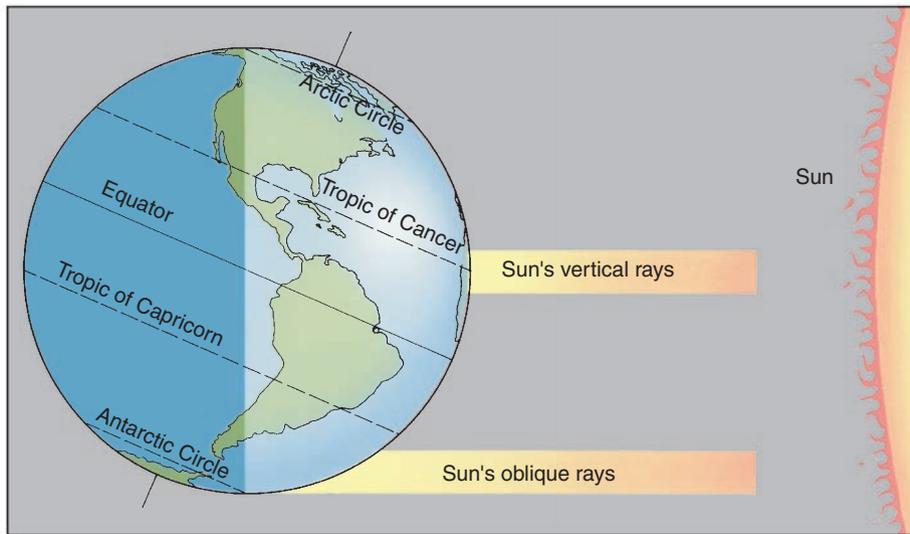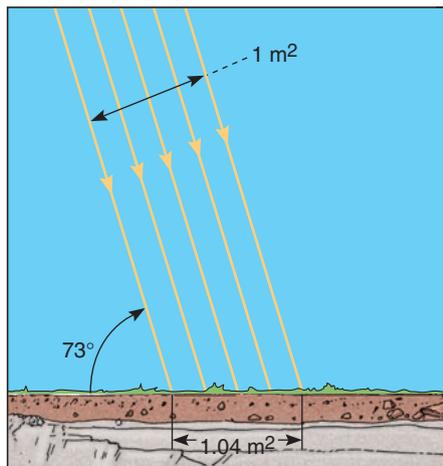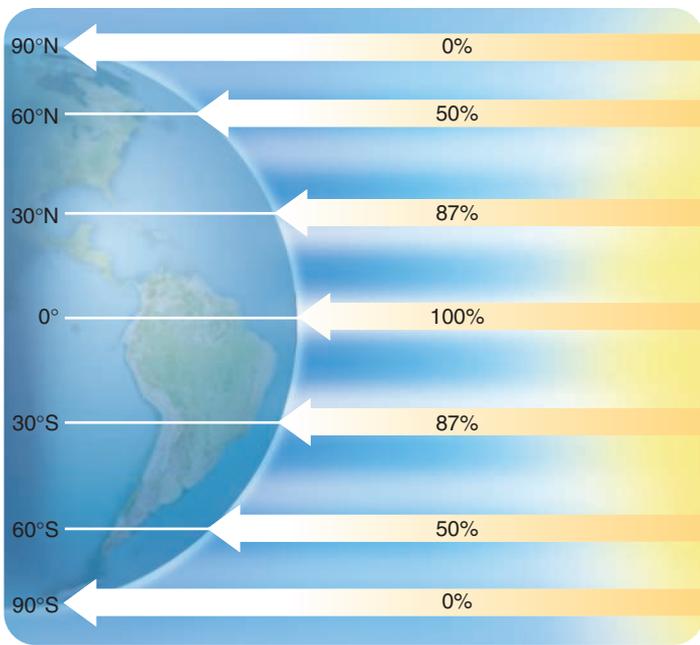
• FIGURE 3.15
(a) The angle at which the sun's rays strike Earth's surface determines the amount of solar energy received per unit of surface area. This amount in turn affects the seasons. The diagram represents the June condition, when solar radiation strikes the surface perpendicularly on the Tropic of Cancer, creating summer conditions in the Northern Hemisphere. In the Southern Hemisphere, the sun's rays are more oblique and spread over larger areas, thus receiving less energy per unit of area, making this the winter hemisphere. **How would a similar figure of Earth–sun relationships in December differ?** The sun's rays in summer (b) and winter (c). In summer the sun appears high in the sky, and its rays hit Earth more directly, spreading out less. In winter the sun appears low in the sky, and its rays spread out over a much wider area, becoming less effective at heating the ground.

under these conditions, a larger portion of the Northern Hemisphere than the Southern Hemisphere remains in daylight. Conversely, a larger portion of the Southern Hemisphere than the Northern Hemisphere remains in darkness. Thus, a person living at Repulse Bay, Canada, north of the Arctic Circle, experiences a full 24 hours of daylight at the June solstice. On the same day, someone living in New York City will experience a longer period of daylight than of darkness. However, someone living in Buenos Aires, Argentina, will have a longer period of darkness than daylight on that day. This day is called the winter solstice in

the Southern Hemisphere. Thus, June 21 is the longest day, with the highest sun angles of the year in the Northern Hemisphere, and the shortest day, with the lowest sun angles of the year, in the Southern Hemisphere.

Now let's imagine the movement of Earth from its position at the June solstice toward a position a quarter of a year later, in September. As Earth moves toward that new position, we can imagine the changes that will be taking place in our three cities. In Repulse Bay, there will be an increasing amount of darkness through July, August, and September. In New York, sunset will be

● **FIGURE 3.16**
The percentage of incoming solar radiation (insolation) striking various latitudes during an equinox date according to Lambert's Law.
How much less solar energy is received at 60° latitude than that received at the equator?

arriving earlier. In Buenos Aires, the situation will be reversed; as Earth moves toward its position in September, the periods of daylight in the Southern Hemisphere will begin to get longer, the nights shorter.

Finally, on or about September 22, Earth will reach a position known as an **equinox** (Latin: *aequus,* equal; *nox,* night). On this date (the autumnal equinox in the Northern Hemisphere), day and night will be of equal length at all locations on Earth. Thus, on the equinox, conditions are identical for both hemispheres. As you can see in ● Figure 3.18, position B, Earth's axis points neither toward nor away from the sun (imagine the axis is pointed at the reader); the circle of illumination passes through both poles, and it cuts Earth in half along its axis.

Imagine again the revolution and rotation of Earth while moving from around September 22 toward a new position another quarter of a year later in December. We can see that in Repulse Bay the nights will be getting longer until, on the winter solstice, which occurs on or about December 21, this northern town will experience 24 hours of darkness (Fig. 3.17, position C). The only natural light at all in Repulse Bay will be a faint glow at noon refracted from the sun below the horizon. In New York, too, the days will get shorter, and the sun will set earlier. Again, we can see that in Buenos Aires the situation is reversed. Around December 21, that city will experience its summer solstice; conditions will be much as they were in New York City in June.

Moving from late December through another quarter of a year to late March, Repulse Bay will have longer periods of daylight, as will New York, while in Buenos Aires the nights will be getting longer. Then, on or about March 20, Earth will again be in an equinox position (the vernal equinox in the Northern Hemisphere) similar to the one in September (Fig. 3.18, position D). Again, days and nights will be equal all over Earth (12 hours each).

TABLE 3.2
Duration of Daylight for Certain Latitudes

| Length of Day (Northern Hemisphere) (read down)			
LATITUDE (IN DEGREES)	**MAR. 20/SEPT. 22**	**JUNE 21**	**DEC. 21**
0.0	12 hr	12 hr	12 hr
10.0	12 hr	12 hr 35 min	11 hr 25 min
20.0	12 hr	13 hr 12 min	10 hr 48 min
23.5	12 hr	13 hr 35 min	10 hr 41 min
30.0	12 hr	13 hr 56 min	10 hr 4 min
40.0	12 hr	14 hr 52 min	9 hr 8 min
50.0	12 hr	16 hr 18 min	7 hr 42 min
60.0	12 hr	18 hr 27 min	5 hr 33 min
66.5	12 hr	24 hr	0 hr
70.0	12 hr	24 hr	0 hr
80.0	12 hr	24 hr	0 hr
90.0	12 hr	24 hr	0 hr
LATITUDE	**MAR. 20/SEPT. 22**	**DEC. 21**	**JUNE 21**
Length of Day (Southern Hemisphere) (read up)			
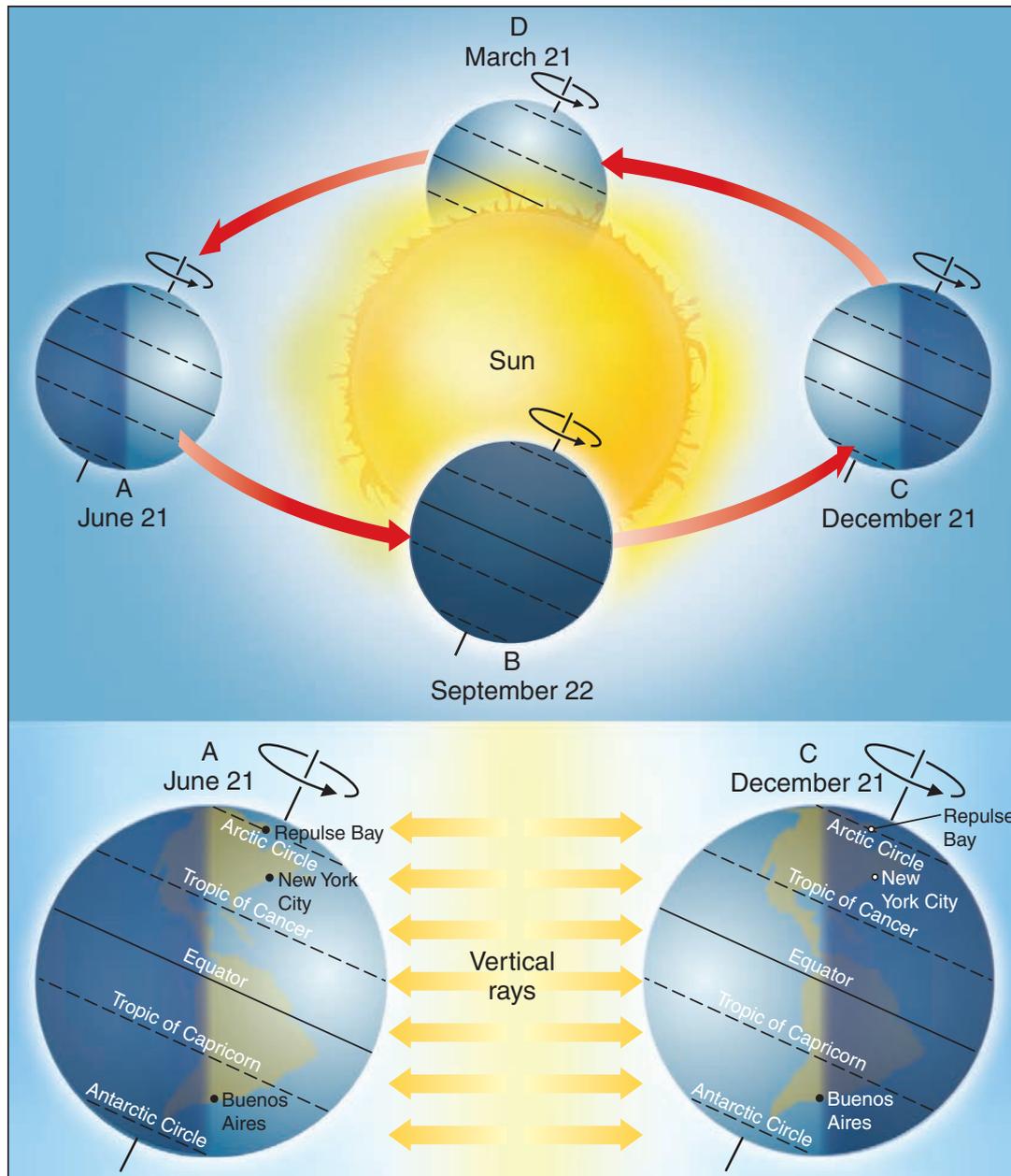
● **FIGURE 3.17**
The geometric relationships between Earth and the sun during the June and December solstices. Note the differing day lengths at the summer and winter solstices in the Northern and Southern Hemispheres.

Finally, moving through another quarter of the year toward the June solstice where we began, Repulse Bay and New York City are both experiencing longer periods of daylight than darkness. The sun is setting earlier in Buenos Aires until, on or about June 21, Repulse Bay and New York City will have their longest day of the year and Buenos Aires its shortest. Further, we can see that around June 21, a point on the Antarctic Circle in the Southern Hemisphere will experience a winter solstice similar to that which Repulse Bay had around December 21 (Fig. 3.17, position A). There will be no daylight in 24 hours, except what appears at noon as a glow of twilight in the sky.

Lines on Earth Delimiting Solar Energy

Looking at the diagrams of Earth in its various positions as it revolves around the sun, we can see that the angle of inclination is important. On June 21, the plane of the ecliptic is directly on 23½°N latitude. The sun's rays can reach 23½° beyond the North Pole, bathing it in sunlight. The **Arctic Circle,** an imaginary line drawn around Earth 23½° from the North Pole (or 66½° north of the equator) marks this limit. We can see from the diagram that all points on or north of the Arctic Circle will experience no darkness on the June solstice and that all points south of the
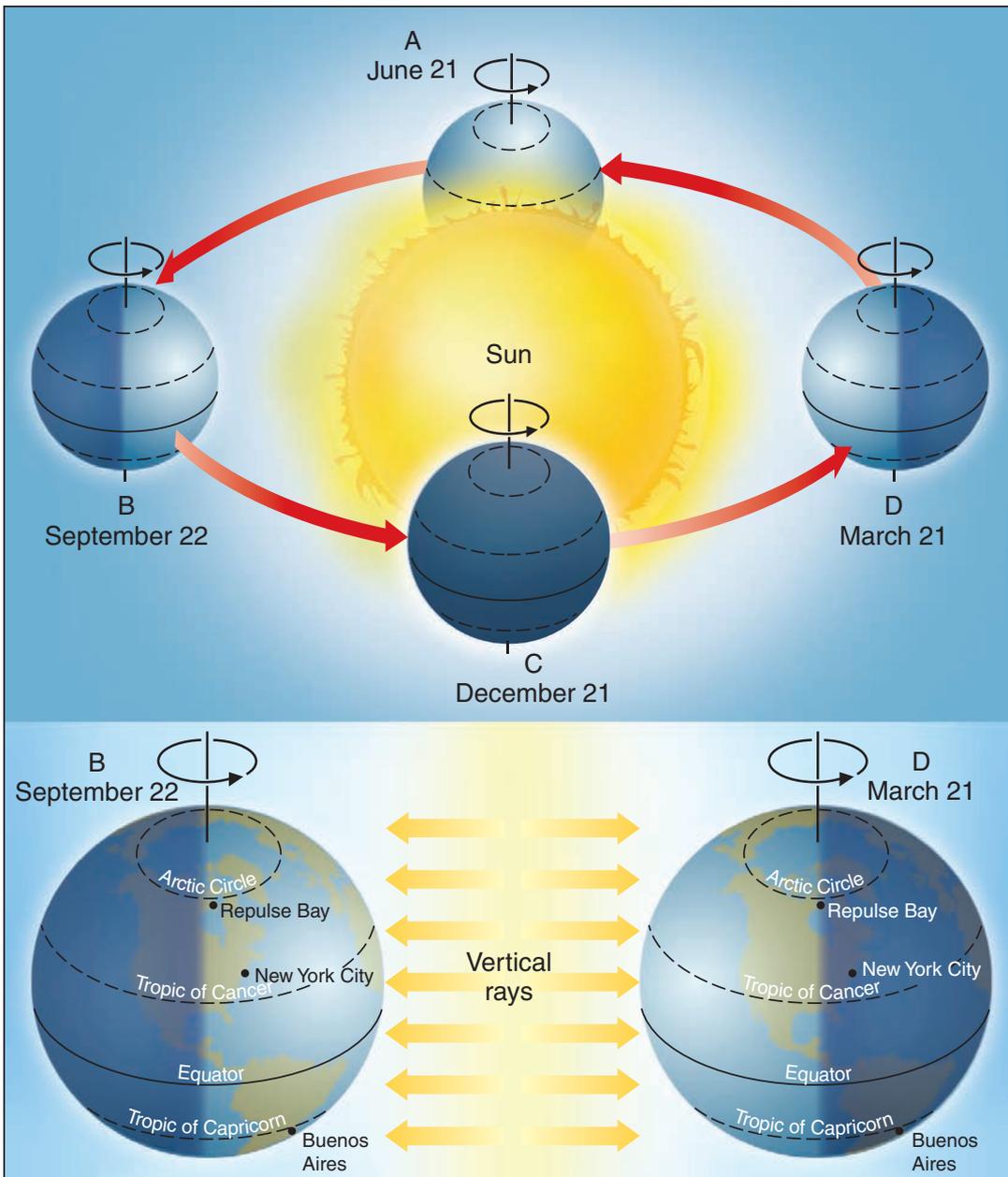
● **FIGURE 3.18**

The geometric relationships between Earth and the sun at the March and September equinoxes. Daylight and darkness periods are 12 hours everywhere because the circle of illumination crosses the equator at right angles and cuts through both poles.

If Earth were not inclined on its axis, would there still be latitudinal temperature variations? Would there be seasons?

Arctic Circle will have some darkness on that day. The **Antarctic Circle** in the Southern Hemisphere (23½° north of the South Pole, or 66½° south of the equator) marks a similar limit.

Furthermore, it can be seen from the diagrams that the sun's **vertical (direct) rays** (rays that strike Earth's surface at right angles) also shift position in relation to the poles and the equator as Earth revolves around the sun. At the time of the June solstice, the sun's rays are vertical, or directly overhead, at noon at 23½° *north* of the equator. This imaginary line around Earth

marks the northernmost position at which the solar rays will ever be directly overhead during a full revolution of our planet around the sun. The imaginary line marking this limit is called the **Tropic of Cancer** (23½°N latitude). Six months later, at the time of the December solstice, the solar rays are vertical, and the noon sun is directly overhead 23½° *south* of the equator. The imaginary line marking this limit is known as the **Tropic of Capricorn** (23½°S latitude). At the times of the March and September equinoxes, the vertical solar rays will strike directly

Using the Sun's Rays to Measure the Spherical Earth—2200 Years Ago

About 240 BC in Egypt, Eratosthenes, a Greek philosopher and geographer, observed that the noonday sun's angle above the horizon changed along with the seasons. Knowing that our planet was spherical, he used geometry and solar observations to make a remarkably accurate estimate of Earth's circumference. A librarian in Alexandria, he read an account of a water well in Syene (today Aswan, Egypt), located to the south about 800 kilometers (500 mi) on the Nile River. On June 21 (summer solstice), this account stated, the sun's rays reached the bottom of the well and illuminated the water. Because the well was vertical, this meant that the sun was directly overhead on that day. Syene was also located very near the Tropic of Cancer, the latitude of the subsolar point on that date.

Eratosthenes had made many observations of the sun's angle over the year, so he knew that the sun's rays were never vertical in Alexandria, and at noon on that day in June a vertical column near the library formed a shadow. Measuring the angle between the column and a line from the column top to the shadow's edge, he found that the sun's angle was 7.2° away from vertical.

Assuming that the sun's rays strike Earth's spherical surface in a parallel fashion, Eratosthenes knew that Alexandria was located 7.2° north of Syene. Dividing the number of degrees in a circle (360°) by 7.2°, he calculated that the two cities were separated by 1/50 of Earth's circumference. The distance between Syene and Alexandria was 5000 stades, with a stade being the distance around the running track at a stadium. Therefore, 5000 stades times 50 meant that Earth must be 250,000 stades in circumference.

Unfortunately in ancient times, stades of different lengths were being used in different regions, and it is not certain which distance Eratosthenes used. A commonly cited stade length is about 0.157 kilometers (515 ft), and in using this measure, the resulting distance estimate would be 39,250 kilometers (24,388 mi). This distance is very close to the actual circumference of the great circle that would connect Alexandria and Syene.
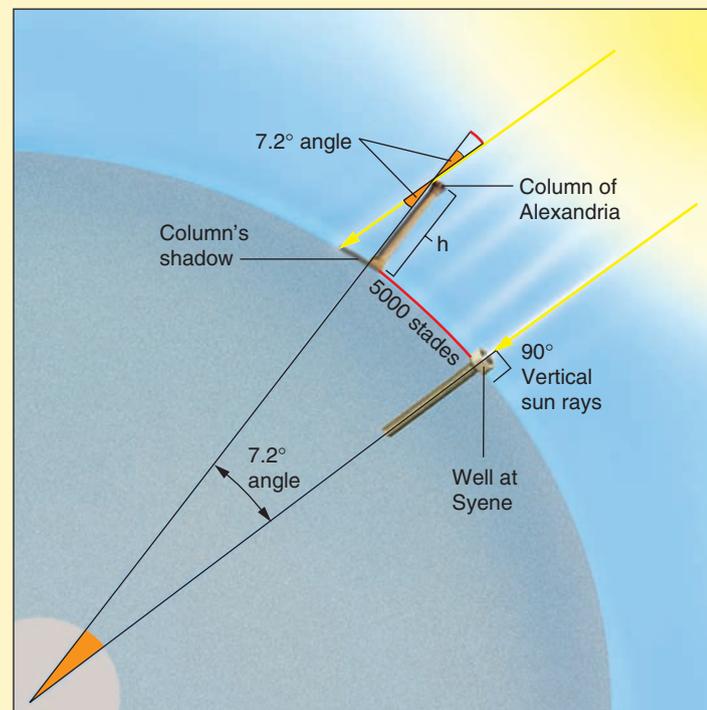
By observing the noon sun angle cast by a column where he lived and knowing that no shadow was cast on that same day in Syene to the south, Eratosthenes used geometry to estimate the Earth's circumference. On a spherical Earth, a 7.2° difference in angle also meant that Syene was 7.2° south in latitude from Alexandria, or 1/50 of Earth's circumference.

at the equator; the noon sun is directly overhead at all points on that line (0° latitude).

Note also that on any day of the year the sun's rays will strike Earth at a 90° angle at only one position, either on or between the two tropics. All other positions that day will receive the sun's rays at an angle of less than 90° (or will receive no sunlight at all).

The Analemma

The latitude at which the noon sun is directly overhead is also known as the sun's **declination.** Thus, if the sun appears directly overhead at 18°S latitude, the sun's declination is 18°S. A figure called an **analemma,** which is often drawn on globes as a big-bottomed "figure 8," shows the declination of the sun throughout the year. A modified analemma is presented in ● Figure 3.19. Thus, if you would like to know where the sun will be directly overhead on April 25, you can look on the analemma and see that it will be at 13°N. The analemma actually charts the passage of the direct rays of the sun over the 47° of latitude that they cover during a year.
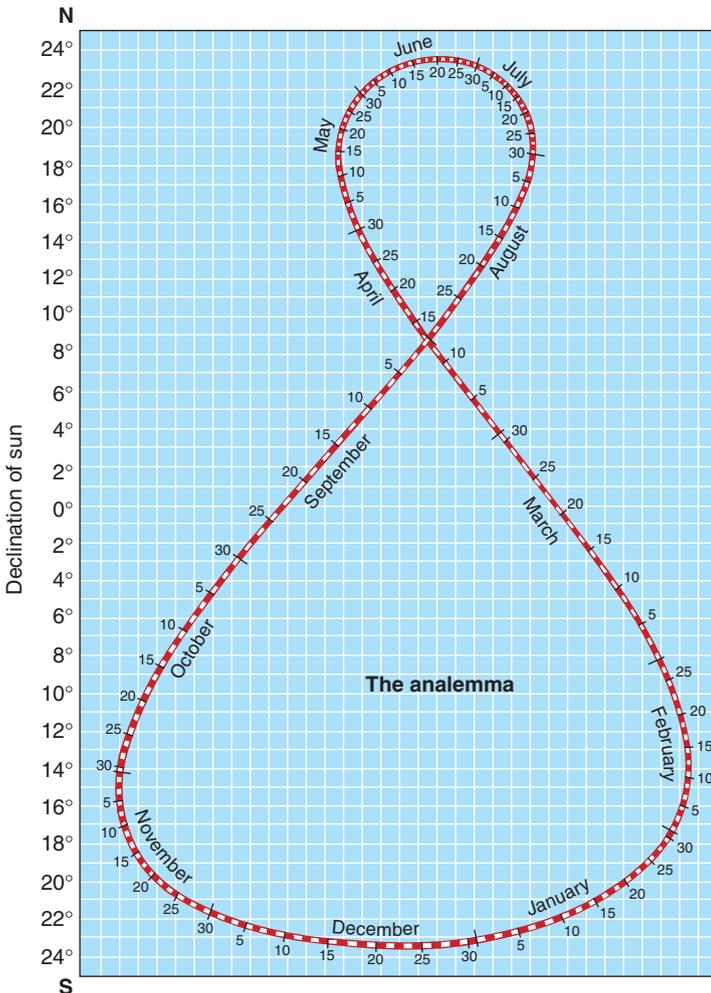
Variations of Insolation with Latitude

Neglecting for the moment the influence of the atmosphere on variations in insolation during a 24-hour period, the amount of energy received by the surface begins after daybreak and increases as Earth rotates toward the time of solar noon. A place will receive its greatest insolation at solar noon when the sun has reached its zenith, or highest point in the sky, for that day. The amount of insolation then decreases as the sun angle lowers toward the next period of darkness. Obviously, at any location, no insolation is received during the darkness hours.

We also know that the amount of daily insolation received at any one location on Earth varies with latitude (see again Fig. 3.16). The seasonal limits of the most direct insolation are used to determine recognizable zones on Earth. Three distinct patterns occur in the distribution of the seasonal receipt of solar energy in each hemisphere. These patterns serve as the basis for recognizing six latitudinal zones, or bands, of insolation and temperature that circle Earth (● Fig. 3.20).

If we look first at the Northern Hemisphere, we may take the Tropic of Cancer and the Arctic Circle as the dividing lines for three of these distinctive zones. The area between the equator and the Tropic of Cancer can be called the *north tropical zone.* Here, insolation is always high but is greatest at the time of the year that the sun is directly overhead at noon. This occurs twice a year, and these dates vary according to latitude (see again Fig. 3.19). The *north middle-latitude zone* is the wide band between the Tropic of Cancer and the Arctic Circle. In this belt, insolation is greatest on the June solstice when the sun reaches its highest noon

● **FIGURE 3.19**
An analemma is used to find the solar declination (latitudinal position) of the vertical noon sun for each day of the year.
What is the declination of the sun on October 30th?

● **FIGURE 3.20**
The equator, the Tropics of Cancer and Capricorn, and the Arctic and Antarctic Circles define six latitudinal zones that have distinctive insolation characteristics.
Which zone(s) would have the least annual variation in insolation? Why?
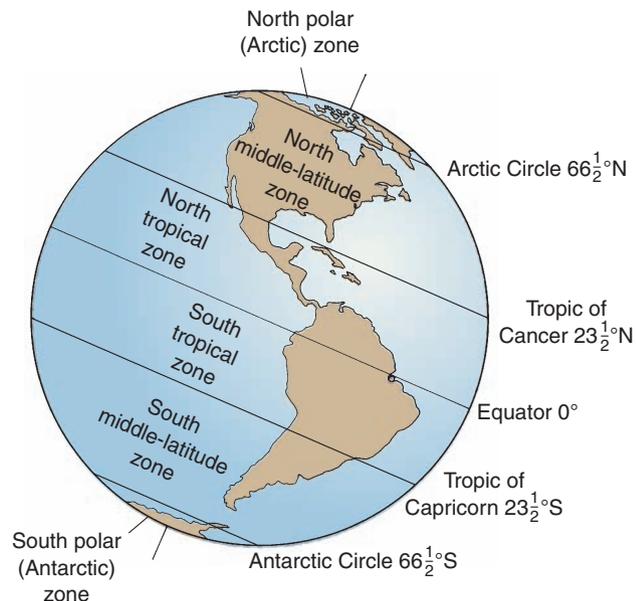
angle and the period of daylight is longest. Insolation is least at the December solstice when the sun is lowest in the sky and the period of daylight the shortest. The north *polar zone,* or *Arctic zone,* extends from the Arctic Circle to the pole. In this region, as in the middle-latitude zone, insolation is greatest at the June solstice, but it ceases during the period that the sun's rays are blocked entirely by the tilt of Earth's axis. This period lasts for 6 months at the North Pole but is as short as 1 day directly on the Arctic Circle.

Similarly, there is a *south tropical zone,* a *south middle-latitude zone*, and a *south polar zone,* or *Antarctic zone,* all separated by the Tropic of Capricorn and the Antarctic Circle in the Southern Hemisphere. These areas get their greatest amounts of insolation at opposite times of the year from the northern zones.

Despite various patterns in the amount of insolation received in these zones, we can make some generalizations. For example, total annual insolation at the top of the atmosphere over a particular latitude remains nearly constant from year to year (the solar constant). Furthermore, annual insolation tends to decrease from lower latitudes to higher latitudes (Lambert's Law together with Beer's Law). The closer to the poles a place is located, the greater will be its seasonal variations caused by fluctuations in insolation.

The amount of insolation received by the Earth system is an important concept in understanding atmospheric dynamics and the distribution of climate, soils, and vegetation across the globe. Such climatic elements as temperature, precipitation, and winds are controlled in part by the amount of insolation received by Earth. People depend on certain levels of insolation for physical comfort, and plant life is especially sensitive to the amount of available insolation. You may have noticed plants that have wilted in too much sunlight or that have grown brown in a dark corner away from a window. Over a longer period of time, deciduous plants have an annual cycle of budding, flowering, leafing, and losing their leaves. This cycle is apparently determined by the fluctuations of increasing and decreasing solar radiation that mark the changing seasons. Even animals respond to seasonal changes. Some animals hibernate; many North American birds fly south toward warmer weather as winter approaches; and many animals breed at such a time that their offspring will be born in the spring, when warm weather is approaching.

Ancient civilizations around the world (from China to Mexico) realized the incredible influence of the solar energy and many societies worshiped the sun, as chief among the pagan gods (• Fig. 3.21). And of course they would—the sun was vital to their survival and they knew it! Most humans do not worship the sun as a god any longer, but it is extremely important to understand and appreciate its role as Earth's ultimate source of energy.

●**FIGURE 3.21**

El Castillo, a Mayan Pyramid at Chichén Itzá, Mexico, was oriented to the annual change in sun angle, as the Maya worshiped the sun. Each side has 91 steps—the number of days separating the solstice and equinox days. On the vernal equinox, the afternoon sun casts a shadow that makes it appear like a giant snake is crawling down the pyramid's north side.

Why would ancient civilizations worship the sun?

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