Vast expanses of moving sand occur in parts of the Sahara Desert. Fed by sandstone formations that slowly release sand particles, the wind-driven sand sheets form an ever-changing landscape of dunes.

The sand sheets of the Sahara are very bright objects, reflecting as much as 40 percent of the sunlight they receive. The proportion of solar energy that is reflected from a surface is termed its albedo. High-albedo surfaces like sand help cool the planet by reflecting large amounts of sunlight back to space.

The long, striking shadows of the caravan in this photo point out another important fact—that the strength of the Sun’s energy depends on its angle in the sky. When the Sun is low, its energy is spread across a larger amount of surface, like the shadows of the dromedaries. When the Sun is overhead, its energy is most intense.

On a global scale, the Earth’s climate is determined by the balance between solar energy absorbed and reflected. On a local or regional scale, climate is determined by how the Sun’s path in the sky varies from day to day and season to season. We’ll have a lot more to say about these effects in this chapter.
Our planet receives a nearly constant flow of solar energy that powers all life processes and most processes of the atmosphere and Earth’s surface. What are the characteristics of this energy? How and where does the Earth and atmosphere absorb this solar energy? How is solar energy converted to heat that is ultimately radiated back to space? How does the Earth–atmosphere system trap heat to produce the greenhouse effect? These are some of the questions we will answer in this chapter.

The Earth’s Global Energy Balance

The Ozone Layer—Shield to Life

High above the Earth’s surface lies an atmospheric layer rich in ozone—a form of oxygen in which three oxygen atoms are bonded together (O₃). Ozone is a highly reactive gas that can be toxic to life and damaging to materials, but high in the atmosphere it serves an essential purpose—sheltering life on the Earth’s surface from powerful ultraviolet radiation emitted by the Sun. Without the ozone layer to absorb this radiation, bacteria exposed at the Earth’s surface would be destroyed, and unprotected animal tissues would be severely damaged.

The ozone layer is presently under attack by air pollutant gases produced by human activity. The most important gases are chlorofluorocarbons, or CFCs—synthetic industrial chemical compounds containing chlorine, fluorine, and carbon atoms. Although CFCs were banned in aerosol sprays in the United States beginning in 1976, they are still used as cooling fluids in some refrigeration systems. When appliances containing CFCs leak or are discarded, their CFCs are released into the air.

In the northern hemisphere, conditions for the formation of an ozone hole are not as favorable. But arctic ozone holes have occurred several times in the past decade, with a strong arctic ozone hole observed in 2005. Atmospheric computer models have projected more such events in the period 2010–2019.

Aerosols inserted into the stratosphere by volcanic activity also can act to reduce ozone concentrations. The June 1991 eruption of Mount Pinatubo, in the Philippines, reduced global ozone in the stratosphere by 4 percent during the following year, with reductions over midlatitudes of up to 9 percent.

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Aerosols inserted into the stratosphere by volcanic activity also can act to reduce ozone concentrations. The June 1991 eruption of Mount Pinatubo, in the Philippines, reduced global ozone in the stratosphere by 4 percent during the following year, with reductions over midlatitudes of up to 9 percent.

A “hole” in the ozone layer was discovered over the continent of Antarctica in the mid-1980s (Figure 2.1). In recent years, the ozone layer there has been found to thin during the early spring of the southern hemisphere, reaching a minimum during the month of September or October. Typically, the ozone hole slowly shrinks and ultimately disappears in early December.

The Antarctic ozone hole of 2006 was the largest on record, covering about 29.5 million km² (about 11.4 million mi²). Low values of ozone are shown in purple ranging through blue, green, and yellow. Ozone concentration is measured in Dobson units, and October 8, 2006, saw its lowest value—85 units.
Since 1978, surface-level ultraviolet radiation has been increasing. Over most of North America, the increase has been about 4 percent per decade. This trend is expected to increase the number of skin cancer cases. Crop yields and some forms of aquatic life may also suffer. Today, we are all aware of the dangers of harmful ultraviolet rays to our skin and the importance of using sunscreen before going outdoors.

In response to the global threat of ozone depletion, 23 nations signed a treaty in 1987 to cut global CFC consumption by 50 percent by 1999. The treaty was effective, and by 1997, stratospheric chlorine concentrations had topped out and started to fall. In 2003, scientists using three NASA satellite instruments and three international ground stations confirmed a slowing in the rate of ozone depletion starting in 1997.

In operation for two decades, the international agreements have had an effect. Though not a reversal of ozone loss, the trend is encouraging. Current predictions show that the ozone layer will be restored by the middle of the century.

Electromagnetic Radiation

All surfaces—from the fiery Sun in the sky to the skin covering our bodies—constantly emit radiation. Very hot objects, such as the Sun or a light bulb filament, give off radiation that is nearly all in the form of light. Most of this energy is visible light, which we perceive with the colors of the rainbow, but the Sun also emits ultraviolet and infrared light that cannot be seen directly.

Cooler objects than the Sun, such as Earth surfaces and even our own bodies, emit heat radiation. So, our planet’s surface and its atmosphere constantly emit heat. Over the long run, the Earth emits exactly as much energy as it absorbs from the sun, creating a global energy balance.

Light and heat are both forms of electromagnetic radiation. You can think of electromagnetic radiation as a collection of waves, of a wide range of wavelengths, that travel away from the surface of an object. Radiant energy can exist at any wavelength. Heat and light are identical forms of electromagnetic radiation except for their wavelengths.

Wavelength is the distance separating one wave crest from the next wave crest, as you can see in Figure 2.2. In this book, we will measure wavelength in micrometers. A micrometer is one millionth of a meter (10⁻⁶ m). The tip of your little finger is about 15,000 micrometers wide. We use the abbreviation µm for the micrometer. The first letter is the Greek letter μ, or µm.

Electromagnetic waves differ in wavelength throughout their entire range, or spectrum (Figure 2.3). Gamma rays and X rays lie at the short-wavelength end of the spectrum. Their wavelengths are normally expressed in nanometers. A nanometer is one one-thousandth of a micrometer, or 10⁻⁹ m, and is abbreviated nm. Gamma and X rays have high energies and can be hazardous to health. Ultraviolet radiation begins at about 10 nm and extends to 400 nm (or 0.4 µm). It can also damage living tissues.

Visible light begins at about 0.4 µm with the color violet. Colors then gradually change through blue, green, yellow, orange, and red, until we reach the end of the visible spectrum at about 0.7 µm. Next is near-infrared radiation, with wavelengths from 0.7 to 1.2 µm. This radiation is very similar to visible light—most of it comes from the Sun. We can’t see near-infrared light because our eyes are not sensitive to radiation beyond about 0.7 µm.

Shortwave infrared radiation also mostly comes from the Sun and lies between 1.2 and 3.0 µm. Middle-infrared radiation, from 3.0 µm to 6 µm, can come from the Sun or from very hot sources on the Earth, such as forest fires and gas well flames.

Next we have thermal infrared radiation, between 6 µm and 300 µm. This is given off by bodies at temperatures normally found at the Earth’s surface. Figure 2.4 shows a thermal infrared image of a suburban scene obtained at night using a special sensor. Here red tones indicate the warmest temperatures and black tones the coldest. Windows appear red because they are warm and radiate more intensely. House walls are intermediate in temperature and appear blue. Roads and driveways are cool, as
2.3 The electromagnetic spectrum

Electromagnetic radiation can exist at any wavelength. By convention, names are assigned to specific wavelength regions.

2.4 A thermal infrared image

This thermal image shows a suburban scene at night. Black and violet tones show lower temperatures, while yellow and red tones show higher temperatures. Ground and sky are coldest, while the windows of the heated homes are warmest.
are the trees, shown in purple tones. Ground and sky are coldest (black).

**GEODISCOVERIES: The Electromagnetic Spectrum**

Expand your vision! Go to this animation and click on parts of the electromagnetic spectrum to reveal images that can’t be sensed directly with your eyes.

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**RADIATION AND TEMPERATURE**

There are two important physical principles to remember about the emission of electromagnetic radiation. The first is that hot objects radiate more energy than cooler objects. The flow of radiant energy from the surface of an object is directly related to the absolute temperature of the surface, measured on the Kelvin absolute temperature scale, raised to the fourth power. So if you double the absolute temperature of an object, it will emit 16 times more energy from its surface. Even a small increase in temperature can mean a large increase in the rate at which radiation is given off by an object or surface.

The second principle is that the hotter the object, the shorter are the wavelengths of radiation that it emits. This inverse relationship between wavelength and temperature means that very hot objects like the Sun emit radiation at short wavelengths. Because the Earth is a much cooler object, it emits radiation with longer wavelengths. This principle explains why the Sun emits light and the Earth emits heat.

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**SOLAR RADIATION**

Our Sun is a ball of constantly churning gases that are heated by continuous nuclear reactions. It is about average in size compared to other stars, and it has a surface temperature of about 6000°C (about 11,000°F). The Sun’s energy travels outward in straight lines or rays at a speed of about 300,000 km (about 186,000 mi) per second—the speed of light. At that rate, it takes the energy about 8 ½ minutes to travel the 150 million km (93 million mi) from the Sun to the Earth.

The rays of solar radiation spread apart as they move away from the Sun. This means that a square meter on Mars will intercept less radiation than on Venus because Mars lies farther from the Sun. The Earth only receives about one-half of one-billionth of the Sun’s total energy output.

Solar energy is generated by nuclear fusion reactions inside the Sun, as hydrogen is converted to helium at very high temperatures and pressures. A vast quantity of energy is generated this way, which finds its way to the Sun’s surface. The rate of solar energy production is nearly constant, so the output of solar radiation also remains nearly constant, as does the amount of solar energy received by the Earth. The rate of incoming energy, known as the solar constant, is measured beyond the outer limits of the Earth’s atmosphere, before any energy has been lost in the atmosphere.

You’ve probably seen the **watt (W)** used to describe the power, or rate of energy flow, of a light bulb or other home appliance. When we talk about the intensity of received (or emitted) radiation, we must take into account both the power of the radiation and the surface area being hit by (or giving off) energy. So we use units of watts per square meter (W/m²). The solar constant has a value of about 1367 W/m². Because there are no common equivalents for this energy flow rate in the English system, we will use only metric units.

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**CHARACTERISTICS OF SOLAR ENERGY**

Let’s look in more detail at the Sun’s output as it is received by the Earth (illustrated in Figure 2.5). Energy intensity is shown on the graph on the vertical scale. Note that it is a logarithmic scale—that is, each whole unit marks an intensity 10 times greater than the one below. Wavelength is shown on the horizontal axis, also on a logarithmic scale.

The left side of Figure 2.5 shows how the Sun’s incoming electromagnetic radiation varies with wavelength. The uppermost line indicates how a “perfect” Sun would supply solar energy at the top of the atmosphere. By “perfect,” we mean a Sun at a temperature of 6000 K radiating as a blackbody—an ideal surface that follows physical theory exactly. The solid line shows the actual output of the Sun as measured at the top of the atmosphere. It is quite close to the “perfect” Sun, except for ultraviolet wavelengths, where the real Sun emits less energy. The Sun’s output peaks in the visible part of the spectrum. We can see that human vision is adjusted to the wavelengths where solar light energy is highest.

The solar radiation actually reaching the Earth’s surface is quite different from the solar radiation measured above the Earth’s atmosphere. This is because solar radiation is both absorbed and scattered by varying amounts at different wavelengths as it passes through the atmosphere.

Molecules and particles in the atmosphere intercept and absorb radiation at particular wavelengths. This atmospheric absorption directly warms the atmosphere in a way that affects the global energy balance, as we will discuss.

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**Shortwave radiation** refers to wavelengths emitted by the Sun, which are in the range of about 0.3 to 3 µm. **Longwave radiation** refers to wavelengths emitted by cooler objects, such as Earth surfaces, which range from about 3 to 30 µm.
toward the end of this chapter. Solar rays can also be \textit{scattered} into different directions when they collide with molecules or particles in the atmosphere. Rays can be diverted back up into space or down toward the surface, and may be scattered several times.

Solar energy received at the surface ranges from about 0.3 µm to 3 µm. This is known as \textit{shortwave radiation}. We will now turn to the longer wavelengths of energy that are emitted by the Earth and atmosphere.

\textbf{LONGWAVE RADIATION FROM THE EARTH}

Remember that both the range of wavelengths and the intensity of radiation emitted by an object depend on the object’s temperature. Because the Earth’s surface and atmosphere are much colder than the Sun, our planet radiates less energy than the Sun and this energy is emitted at longer wavelengths.

The right side of Figure 2.5 shows exactly that. The upper line shows the radiation of a blackbody at a temperature of about 300 K (23°C, 73°F), which is a good approximation for the Earth as a whole. At this temperature, radiation ranges from about 3 to 30 µm and peaks at about 10 µm in the thermal infrared region. This thermal infrared radiation emitted by the Earth is \textit{longwave radiation}.

Beneath the blackbody curve is an irregular series of peaks that show upwelling energy emitted by the
Earth and atmosphere as measured at the top of the atmosphere. Some wavelengths in this range seem to be missing, especially between 6–8 µm, 14–17 µm, and above 21 µm. These wavelengths are almost completely absorbed by the atmosphere before they can escape. Water vapor and carbon dioxide are the main absorbers, playing a large part in the greenhouse effect, which we will discuss shortly.

There are still three regions where outgoing energy flow from the Earth to space is significant—4 to 6 µm, 8 to 14 µm, and 17 to 21 µm. We call these windows through which longwave radiation leaves the Earth and flows to space.

THE GLOBAL RADIATION BALANCE

The Earth constantly absorbs solar shortwave radiation and emits longwave radiation. Figure 2.6 presents a diagram of this energy flow process, which we refer to as the Earth’s global radiation balance.

The Sun provides a nearly constant flow of shortwave radiation that is intercepted by the Earth. Scattering...
Although the flow of solar radiation to the Earth as a whole remains constant, different places on the planet receive different amounts of energy at different times. What causes this variation?

Incoming solar radiation is known as **insolation**. It is a rate of flow of energy and is measured in units of watts per square meter (W/m²). Daily insolation is the average flow rate over a 24-hour day, while annual insolation is the average flow rate over the entire year.

Insolation depends on the angle of the Sun above the horizon. It is greatest when the Sun is directly overhead, and it decreases when the Sun is low in the sky, since the same amount of solar energy is spread out over a greater area of ground surface (Figure 2.7).

### Insolation over the Globe

Most natural phenomena on the Earth’s surface—from the downhill flow of a river to the movement of a sand dune to the growth of a forest—are powered by the Sun, either directly or indirectly. It is the power source for wind, waves, weather, rivers, and ocean currents, as we will see here and in later chapters.

#### 2.7 Solar intensity and Sun angle

The intensity of the solar beam depends on the angle between the beam and the surface.

- **One unit of surface area**
  - Sunlight, represented by the flashlight, is most intense when the beam is vertical.

- **1.4 units of surface area**
  - One unit of light is dispersed over 1.4 units of surface area.
  - When the beam strikes the surface at an angle of 45°, it covers a larger surface, and so it is less intense.

- **2 units of surface area**
  - One unit of light is dispersed over 2 units of surface area.
  - At 30°, the beam covers an even greater surface and is even weaker.

- **Because the angle of the solar beam striking the Earth varies with latitude, insolation is strongest near the Equator and weakest near the poles.**
The Sun’s Noon Angle and the Length of Day

Imagine yourself watching the Earth from a point far out in space, where it is easy to see how both the Sun’s angle at noon and the length of day vary with the seasons and latitude for any point on Earth. An animation.

DAILY INSOLATION THROUGH THE YEAR

Daily insolation at a location depends on two factors: (1) the angle at which the Sun’s rays strike the Earth, and (2) how long the place is exposed to the rays. In Chapter 1 we saw that both of these factors are controlled by latitude and the time of year. At midlatitude locations in summer, for example, days are long and the Sun rises to a position high in the sky, heating the surface more intensely.

How does the angle of the Sun vary during the day? It depends on the Sun’s path. Near noon, the Sun is high above the horizon—the Sun’s angle is greater, and so insolation is higher. Figure 2.8 shows the typical conditions found in midlatitudes in the northern hemisphere, for example, at New York or Denver. An observer standing on a wide plain will see a small area of the Earth’s surface bounded by a circular horizon. The Earth’s surface appears flat, and the Sun seems to travel inside a vast dome in the sky.

Comparing the three paths shown in the figure, we find that both the length of time the Sun is in the sky and the angle of the Sun during the main part of the day change with the time of year. At the June solstice, average daily insolation will be greatest, since the Sun is in the sky longer and reaches higher elevations. At the December solstice, daily insolation will be least, with a shorter daily path and lower elevations. At the equinox, the insolation will be intermediate.

Figure 2.9 shows the Sun’s path for three other latitudes. At the North Pole, the Sun moves in a circle in the sky at an elevation that changes with the seasons. At the Equator, the Sun is always in the sky for 12 hours, but its noon angle varies through the year. At the Tropic of Capricorn, the Sun is in the sky longest and reaches its highest elevations at the December solstice.

Based on this analysis, daily insolation will vary strongly with season at most latitudes. As shown in Figure 2.10, daily insolation at 40° will range from about 160 W/m² on the December solstice to about 460 W/m² on the June solstice. Insolation drops to zero at the North Pole.
2.9 The Sun's path at the North Pole, Equator, and Tropic of Capricorn
Let’s look first at the real case of a tilted axis. We can see that annual insolation varies smoothly from the Equator to the pole and is greater at lower latitudes. But high latitudes still receive a considerable flow of solar energy—the annual insolation value at the pole is about 40 percent of the value at the equator.

Now let’s look at what would happen if the Earth’s axis was not tilted. With the axis perpendicular to the plane of the ecliptic, there are no seasons. Annual insolation is very high at the Equator because the Sun passes directly overhead at noon every day throughout the year. Annual insolation at the poles is zero because the Sun’s rays always skirt the horizon.

We can see that without a tilted axis our planet would be a very different place. The tilt redistributes a very significant portion of the Earth’s insolation from the equatorial regions toward the poles. So even though the pole does not receive direct sunlight for six months of the year, it still receives nearly half the amount of annual solar radiation as the Equator.

WORLD LATITUDE ZONES

The seasonal pattern of daily insolation provides a convenient way to divide the globe into broad latitude zones (Figure 2.12) that we will use in this book. The equatorial zone encompasses the Equator and covers the latitude belt roughly 10° north to 10° south. Here the Sun provides intense insolation throughout most of the year, and days and nights are of roughly equal
2.12 World latitude zones

A geographer’s system of latitude zones, based on the seasonal patterns of daily insolation observed over the globe.

▲ Subarctic zone  Much of the subarctic zone is covered by evergreen forest, seen here with a ground cover of snow. Near Churchill, Hudson Bay region, Canada (National Geographic Image Collection).

▲ Midlatitude zone  A summer midlatitude landscape in the Tuscany region of Italy (National Geographic Image Collection).

▲ Tropical zone  The tropical zone is the home of the world’s driest deserts. Pictured here is the Rub’ al Khali, Saudi Arabia (National Geographic Image Collection).

▲ Equatorial zone  An equatorial rainforest, as seen along a stream in the Gunung Palung National Park, Borneo, Indonesia.
length. Spanning the Tropics of Cancer and Capricorn are the tropical zones, ranging from latitudes 10° to 25° north and south. A marked seasonal cycle exists in these zones, combined with high annual insolation.

Moving toward the poles, we come to the subtropical zones, which lie roughly between the latitudes 25° to 35° north and south. These zones have a strong seasonal cycle and a large annual insolation. The midlatitude zones are next, between 35° and 55° north and south latitude. The length of daylight varies significantly from winter to summer here, so seasonal contrasts in insolation are quite strong. As a result, these regions experience a large range in annual surface temperature.

The subantarctic and subantarctic zones border the midlatitude zones at 55° to 60° north and south latitudes. The arctic and antarctic zones lie between latitudes 60° and 75° N and S, astride the Arctic and Antarctic Circles. These zones have an extremely large yearly variation in day lengths, yielding enormous contrasts in insolation over the year. Finally, the north and south polar zones range from about 75° latitude to the poles. They experience the greatest seasonal insolation contrast of all, and have 24-hour days or nights for much of the year.

### Composition of the Atmosphere

The Earth is surrounded by air—a mixture of various gases that reaches up to a height of many kilometers. This envelope of air makes up our atmosphere (Figure 2.13). It is held in place by the Earth’s gravity. Almost all the atmosphere (97 percent) lies within 30 km (19 mi) of the Earth’s surface. The upper limit of the atmosphere is at a height of approximately 10,000 km (about 6000 mi) above the Earth’s surface—a distance that is nearly as large as Earth’s diameter.

The proportion of gases in dry air is highly uniform up to an altitude of about 80 km (50 mi). About 99 percent of pure, dry air is nitrogen (about 78 percent by volume) and oxygen (about 21 percent). These two main component gases of the lower atmosphere are perfectly mixed, so pure, dry air behaves as if it is a single gas with very definite physical properties.

Nitrogen gas is a molecule consisting of two nitrogen atoms (N₂). It does not easily react with other substances. Soil bacteria do take up very small amounts of nitrogen, which can be used by plants, but otherwise nitrogen is largely a “filler,” adding inert bulk to the atmosphere.

In contrast, oxygen gas (O₂) is chemically very active, combining readily with other elements in the process of oxidation. Fuel combustion is a rapid form of oxidation, while certain types of rock decay (weathering) are very slow forms of oxidation. Living tissues require oxygen to convert foods into energy.

The remaining 1 percent of dry air is mostly argon, an inactive gas of little importance in natural processes, with a very small amount of carbon dioxide (CO₂), amounting to about 0.0385 percent. Although the amount of CO₂ is small, it is a very important atmospheric gas because it absorbs much of the incoming shortwave radiation from the Sun and outgoing longwave radiation from the Earth. The greenhouse effect is caused when longwave radiation is absorbed by CO₂ molecules in the lower atmosphere, which reradiate some of that heat back to the surface. Carbon dioxide is also used by green plants, which convert it to its chemical compounds to build up their tissues, organs, and supporting structures during photosynthesis.

Water vapor is another important atmospheric gas. Individual water vapor molecules mix freely with other atmospheric gases, but water vapor can vary highly in concentration. Water vapor usually makes up less than 1 percent of the atmosphere, but under very warm, moist conditions, as much as 2 percent of the air can be water vapor. Since it is a good absorber of heat radiation, like carbon dioxide, it plays a major role in warming the lower atmosphere and enhancing the greenhouse effect.

Another small, but important, constituent of the atmosphere is ozone, which we described in our Eye on Global Change opening feature. Ozone in the upper atmosphere is beneficial because it shields life at the Earth’s surface from harmful solar ultraviolet radiation. But in the lowest layers of the atmosphere, ozone is an air pollutant that damages lung tissue and aggravates bronchitis, emphysema, and asthma.

### Sensible Heat and Latent Heat Transfer

The most familiar form of heat storage and transport is known as sensible heat—it’s what you feel when you touch a warm object. When we use a thermometer, we are measuring sensible heat. Sensible heat transfer
moves heat from warmer to colder objects by conduction when they are in direct contact. Sensible heat is also transferred by convection when a fluid such as the atmosphere or ocean carries heat energy away from a surface.

In contrast, latent heat—or hidden heat—cannot be measured by a thermometer. It is heat that is taken up and stored as molecular motion when a substance changes state from a solid to a liquid, from a liquid to a gas, or from a solid directly to a gas. For example, when liquid water changes to water vapor, or ice changes to liquid water, heat energy is absorbed from the surroundings. This is why sweat cools the skin. Latent heat energy is stored in free fluid motion of the liquid water molecules or in the fast random motion of free water vapor molecules. When the vapor turns back to a liquid or solid, the latent heat is released, warming the surroundings.

In the Earth–atmosphere system, latent heat transfer occurs when water evaporates from a moist land surface or from open water, moving heat from the surface to the atmosphere. That latent heat is later released as sensible heat, often far away, when the water vapor condenses to form water droplets or snow crystals. On a global scale, latent heat transfer is a very important mechanism for transporting large amounts of heat from one region of the Earth to another.

**SOLAR ENERGY LOSSES IN THE ATMOSPHERE**

Let’s examine the flow of insolation through the atmosphere on its way to the surface. Figure 2.14 gives typical values for losses of incoming shortwave radiation in the solar beam as it penetrates the atmosphere. Gamma rays and X rays from the Sun are almost completely absorbed by the thin outer layers of the atmosphere, while much of the ultraviolet radiation is also absorbed, particularly by ozone.

As the radiation moves deeper through denser layers of the atmosphere, it can be scattered by gas molecules, dust, or other particles in the air, deflecting it in any direction. Apart from this change in direction, it is unchanged. Scattered radiation moving in all directions through the atmosphere is known as diffuse radiation. Some scattered radiation flows down to the Earth’s surface, while some flows upward. This upward flow of diffuse radiation escaping back to space, also known as diffuse reflection, amounts to about 3 percent of incoming solar radiation.

What about absorption? As we saw earlier, molecules and particles can absorb radiation as it passes through the atmosphere. Carbon dioxide and water are the biggest absorbers, but because the water vapor content of air can vary greatly, absorption also varies from one global environment to another. About 17 percent of incoming

**The Global Energy System**

Human activity around the globe has changed the planet’s surface cover and added carbon dioxide to the atmosphere. Have we irrevocably shifted the balance of energy flows? Is our Earth absorbing more solar energy and becoming warmer? Or is it absorbing less and becoming cooler? If we want to understand human impact on the Earth–atmosphere system, then we need to examine the global energy balance in detail.

The flow of energy from the Sun to the Earth and then back out into space is a complex system. Solar energy is the ultimate power source for the Earth’s surface processes, so when we trace the energy flows between the Sun, surface, and atmosphere, we are really studying how these processes are driven.
solar radiation is absorbed, raising the temperature of atmospheric layers. After taking into account absorption and scattering, about 80 percent of the incoming solar radiation reaches the ground.

Clouds can greatly increase the amount of incoming solar radiation reflected back to space. Reflection from the bright white surfaces of thick low clouds deflects about 30 to 60 percent of incoming radiation back into space. Clouds also absorb as much as 5 to 20 percent of the radiation.

When accounting for both cloudy skies and clear skies on a global scale, only about 50 percent of the total insolation at the top of the atmosphere reaches the surface. When this energy strikes the surface, it can be either absorbed or scattered upward. Absorption heats the surface, raising the surface temperature. The scattered radiation reenters the atmosphere, and much of it passes through, directly to space.

**ALBEDO**

The proportion of shortwave radiant energy scattered upward by a surface is called its albedo. Snow and ice have high albedos (0.45 to 0.85), reflecting most of the solar radiation that hits them and absorbing only a small amount. In contrast, a black pavement, which has a low albedo (0.05), absorbs nearly all the incoming solar energy (Figure 2.15). Water also has a low albedo (0.02), unless the Sun illuminates it at a low angle, producing Sun glint. The energy absorbed by a surface warms the air immediately above it by conduction and convection, so surface temperatures are warmer over low-albedo than over high-albedo surfaces. Fields, forests, and bare ground have intermediate albedos, ranging from 0.03 to 0.25.

The Earth and atmosphere system, taken as a whole, has an albedo of between 0.29 and 0.34. This means that our planet sends back to space slightly less than one-third of the solar radiation it receives. It also means that our planet absorbs slightly more than two-thirds of the solar radiation it receives. This balance between reflected and absorbed solar radiation is what determines the overall temperature of Earth.

**COUNTERRADIATION AND THE GREENHOUSE EFFECT**

As well as being warmed by shortwave radiation from the Sun, the Earth’s surface is significantly heated by the longwave radiation emitted by the atmosphere and absorbed by the ground. Let’s look at this in more detail.

Figure 2.16 shows the energy flows between the surface, atmosphere, and space. On the left we can see the flow of shortwave radiation from the Sun to the surface. Some of this radiation is reflected back to space, but much is absorbed, warming the surface.

Meanwhile, the Earth’s surface emits longwave radiation upwards. Some of this radiation escapes directly to space, while the remainder is absorbed by the atmosphere.

What about longwave radiation emitted by the atmosphere? Although the atmosphere is colder than the surface, it also emits longwave radiation, which is emitted in all directions, and so some radiates upward to space while the remainder radiates downward toward the Earth’s surface. We call this downward flow counterradiation. It replaces some of the heat emitted by the surface.

Counterradiation depends strongly on the presence of carbon dioxide and water vapor in the atmosphere. Remember that much of the longwave radiation emitted upward from the Earth’s surface is absorbed by these two gases. This absorbed energy raises the temperature of the atmosphere, causing it to emit more counterradiation. So, the lower atmosphere, with its longwave-absorbing gases, acts like a blanket that traps heat underneath it. Cloud layers, which are composed of tiny water droplets, are even more important than carbon dioxide and water vapor in producing a blanketing effect because liquid water is also a strong absorber of longwave radiation.

This mechanism, in which the atmosphere traps longwave radiation and returns it to the surface through counterradiation, is termed the greenhouse effect (Figure 2.17). Unfortunately, the term greenhouse is not quite accurate. Like the atmosphere, the window glass in a greenhouse is transparent to solar shortwave radiation while absorbing and reradiating longwave radiation. But a greenhouse is warmed mainly by keeping the warm air inside the greenhouse from mixing with the outside air, not by counterradiation from the glass.

**GLOBAL ENERGY BUDGETS OF THE ATMOSPHERE AND SURFACE**

Although energy may change its form from shortwave to longwave radiation or to sensible heat or latent heat, it cannot be created or destroyed. Like a household budget of income and expenses, the energy flows between the Sun and the Earth’s atmosphere and surface must balance over the long term. The global energy budget shown in Figure 2.18 takes into account all the important energy flows and helps us to understand how changes in these flows might affect the Earth’s climate. It uses a scale in which the amount of incoming solar radiation is represented as 100 units.

Let’s look first at the top of the atmosphere, where we see the balance for the Earth–atmosphere system as a whole. Incoming solar radiation (100 units) is balanced
2.15 Albedo contrasts

▲ Bright snow  A layer of new, fresh snow has a high albedo, reflecting most of the sunlight it receives. Only a small portion is absorbed (National Geographic Image Collection).

▼ Water  Water absorbs solar radiation and has a low albedo unless the radiation strikes the water surface at a low angle. In that case, Sun glint raises the albedo.

▼ Blacktop road  Asphalt paving reflects little light, so it appears dark or black and has a low albedo. It absorbs nearly all of the solar radiation it receives.
2.16 Counterradiation and the greenhouse effect

Shortwave radiation passes through the atmosphere and is absorbed or reflected at the surface. Absorption warms the surface, which emits longwave radiation. Some of this flow passes directly to space (A), but most is absorbed by the atmosphere (B). In turn, the atmosphere radiates longwave energy back to the surface as counterradiation (C) and also to space (D). The counterradiation produces the greenhouse effect.

2.17 A greenhouse and the greenhouse effect

Water vapor and carbon dioxide act like glass, allowing shortwave radiation through but absorbing and radiating longwave radiation.
2.18 The global energy balance

Energy flows continuously among the Earth’s surface, atmosphere, and space. The relative size of each flow is based on an arbitrary “100 units” of solar energy reaching the top of the Earth’s atmosphere. The difference between solar energy absorbed by the Earth system (100 units incoming – 31 reflected = 69 absorbed) and the energy absorbed at the surface (144 units) is the energy (75 units) that is recycled within the Earth system (144 – 69 = 75). The larger this number, the warmer is the Earth system’s climate.

by exiting shortwave reflection from the Earth’s surface and atmosphere and outgoing longwave radiation coming from the atmosphere and surface.

The atmosphere’s budget is also balanced, since it receives 152 units and loses 152 units. Received energy includes absorbed incoming solar radiation, absorbed longwave radiation from the surface, and latent and sensible heat transfer from the surface. The atmosphere loses longwave energy by radiation to space and counterradiation to the surface.

The surface receives 144 units and loses 144 units. Incoming energy consists of direct solar radiation absorbed at the surface and longwave radiation from the atmosphere. Exiting energy includes latent and sensible heat transfer to the atmosphere and longwave radiation to the atmosphere and space.

The greenhouse effect is readily visible in the two largest arrows in the center of the figure. The surface loses 102 units of longwave energy, but receives 95 units of counterradiation from the atmosphere. These flows amount to a loop that traps and returns most of the heat radiation leaving the surface, keeping surface temperatures warm.

CLIMATE AND GLOBAL CHANGE

The global energy budget helps us understand how global change might affect the Earth’s climate. For example, suppose that clearing forests for agriculture and turning agricultural lands into urban and suburban areas decreases surface albedo. In that case, more energy would be absorbed by the ground, raising its temperature. That, in turn, would increase the flow of surface longwave radiation to the atmosphere, which would be absorbed and would then boost counterradiation. The total effect would probably be to amplify warming through the greenhouse effect.

What if industrial aerosols cause more low, thick clouds to form? Low clouds increase shortwave reflection back to space, causing the Earth’s surface and atmosphere to cool. What about increasing condensation trails from jet aircraft? These could cause more high, thin clouds, which absorb more longwave energy and make the atmosphere warmer, boosting counterradiation and increasing the greenhouse effect. The energy flow linkages between the Sun, surface, atmosphere, and space are critical components of our climate system, and human activities can modify these flows significantly.
Net Radiation, Latitude, and the Energy Balance

Although the energy budgets of the Earth’s surface and atmosphere are in balance overall, their budgets do not have to balance at each particular place on the Earth, nor do they have to balance at all times. At night, for example, there is no incoming radiation from the Sun, yet the Earth’s surface and atmosphere still emit outgoing radiation.

**Net radiation** is the difference between all incoming radiation and all outgoing radiation. In places where radiant energy flows in faster than it flows out, net radiation is positive, providing an energy surplus. In other places, net radiation can be negative. For the entire Earth and atmosphere, the net radiation is zero over a year.

We saw earlier that solar energy input varies strongly with latitude. What is the effect of this variation on net radiation? To answer this question, let’s look at Figure 2.19, which shows the net radiation profile from pole to pole. Between about 40° N and 40° S there is a net radiant energy gain, labeled “energy surplus.” In other words, incoming solar radiation exceeds outgoing longwave radiation throughout the year. Poleward of 40° N and 40° S, the net radiation is negative and is labeled “energy deficit”—meaning that outgoing longwave radiation exceeds incoming shortwave radiation.

If you examine the graph carefully, you will find that the area labeled “surplus” is equal in size to the combined areas labeled “deficit.” So the net radiation for the Earth’s surface as a whole is zero, as expected, with global incoming shortwave radiation exactly balancing global outgoing longwave radiation.

Because there is an energy surplus at low latitudes and an energy deficit at high latitudes, energy will flow from low latitudes to high. This energy is transferred poleward as latent and sensible heat—warm ocean water and warm, moist air move poleward, while cooler water and cooler, drier air move toward the Equator.

We’ll return to these flows in later chapters. But keep in mind that this **poleward heat transfer**, driven by the imbalance in net radiation between low and high latitudes, is the power source for broad-scale atmospheric circulation patterns and ocean currents. Without this circulation, low latitudes would heat up and high latitudes would cool down until a radiative balance was achieved, leaving the Earth with much more extreme temperature contrasts—very different from the planet that we are familiar with now. Figure 2.20 illustrates some of the ways that natural processes and human uses are driven by solar power.
2.20 Solar power

Wave erosion Ocean waves, powered by the Sun through the Earth’s wind system, attack and erode the coastline, carving distinctive coastal landforms.

Solar-powered call box This emergency telephone is powered by the solar cell atop its pole.
Water power The hydrologic cycle, powered by solar evaporation of water over oceans, generates runoff from rainfall that erodes and deposits sediment.
The Earth’s global radiation balance is the primary determinant of long-term surface temperature, which is of great importance to life on Earth. Because this balance can be affected by human activities, such as converting forests to pastur-eland or releasing greenhouse gases into the atmosphere, it is important to monitor the Earth’s radiation budget over time as accurately as possible.

For nearly 20 years, NASA has studied the Earth’s radiation budget from space. An ongoing NASA experiment entitled CERES—Clouds and the Earth’s Radiant Energy System—is placing a new generation of instruments in space that scan the Earth and measure the amount of shortwave and longwave radiation leaving the Earth at the top of the atmosphere.

Figure 2.21 shows global reflected solar energy and emitted longwave energy averaged over the month of March 2000 as obtained by CERES. The top image shows average shortwave flux (“flux” means “flow”), ranging from 0 to 210 W/m². The largest flows occur over regions of thick clouds near the Equator, where the bright, white clouds reflect much of the solar radiation back to space. In the midlatitudes, persistent cloudiness during this month also shows up as light tones. Tropical deserts, the Sahara for example, are also bright. Snow and ice surfaces in polar regions are quite reflective, but in March the amount of radiation received in polar regions is low. As a result, they don’t appear as bright in this image. Oceans, especially where skies are clear, absorb solar radiation and thus show low shortwave fluxes.

Longwave flux is shown in the bottom image on a scale from 100 to 320 W/m². Cloudy equatorial regions have low values, showing the blanketing effect of thick clouds that trap longwave radiation beneath them. Warm tropical oceans in regions of clear sky emit the most longwave flux. Poleward, surface and atmospheric temperatures drop, so longwave energy emission also drops significantly.

As you can see from these images, clouds are very important determiners of the global radiation balance. A primary goal of the CERES experiment is to learn more about the Earth’s cloud cover, which changes from minute to minute and hour to hour. This knowledge can be used to improve global climate models that predict the impact of human and natural change on the Earth’s climate.

The most important contribution of CERES, however, is continuous and careful monitoring of the Earth’s radiant energy flows. In this way, small, long-term changes, induced by human or natural change processes, can be detected in spite of large variations in energy flows from place to place and time to time caused by clouds.
A Look Ahead

The Earth’s energy balance is a sensitive one involving many factors that determine how energy is transmitted and absorbed. Have human activities already altered the components of the planetary radiation balance? Scientists have shown convincingly that industrial releases of certain gases, such as carbon dioxide, have enhanced the greenhouse effect, causing global temperatures to warm. Human habitation, through cultivation and urbanization of land, has raised surface albedo and affected the transfer of latent and sensible heat to the atmosphere, modifying the global energy balance. But to understand these effects and others fully requires further study of the processes of heating and cooling of the Earth’s atmosphere, lands, and oceans. Our next chapter concerns air temperature and how and why it varies daily and annually depending on the surface energy balance.

Web Links

View NASA’s images of Earth acquired by astronauts and orbiting satellites. Explore energy balance climate models. Find out more about the CERES instrument and mission. Get the details on stratospheric ozone depletion.

IN REVIEW THE EARTH’S GLOBAL ENERGY BALANCE

- The ozone (O3) layer in the upper atmosphere absorbs solar ultraviolet radiation, shielding surface life from these harmful rays. Industrial chlorofluorocarbons (CFCs) speed the breakdown of ozone, reducing the amount of shielding. During certain conditions, an ozone hole of reduced ozone concentration forms over the Antarctic continent.
- Electromagnetic radiation is a form of energy emitted by all objects. The wavelength of the radiation determines its characteristics. The hotter an object, the shorter the wavelengths of the radiation and the greater the amount of radiation that it emits.
- Radiation emitted by the Sun includes ultraviolet, visible, near-infrared, and shortwave infrared radiation. Thermal infrared radiation, which is emitted by Earth surfaces, is familiar as heat. The atmosphere absorbs and scatters radiation in certain wavelength regions. Radiation flows are measured in watts per square meter.
- The amount of radiation emitted by an object increases very rapidly with its temperature. The wavelengths emitted decrease with increasing temperature.
- Continuous nuclear reactions within the Sun emit vast quantities of energy, largely in the form of light. The Earth receives solar radiation at a near-constant rate known as the solar constant. Solar radiation is strongest in the wavelength range of visible light.
- Molecules and particles in the atmosphere both absorb and scatter incoming shortwave radiation. The Earth’s surface and atmosphere emit longwave radiation.
- The Earth continuously absorbs and scatters solar shortwave radiation and emits longwave radiation. In the long run, the gain and loss of radiant energy remains in a global radiation balance, and the Earth’s average temperature remains constant.
- Insolation, the rate of solar radiation flow available at a location at a given time, is greater when the Sun is higher in the sky. Daily insolation is also greater when the period of daylight is longer.
- Near the Equator, daily insolation is greater at the equinoxes than at the solstices. Between the tropics and poles, the Sun rises higher in the sky and stays longer in the sky at the summer solstice than at the equinox and longer at the equinox than at the winter solstice.
- Annual insolation is greatest at the Equator and least at the poles. However, the poles still receive 40 percent of the annual radiation received at the Equator.
- The pattern of annual insolation with latitude leads to a natural naming convention for latitude zones: equatorial, tropical, subtropical, midlatitude, subarctic (subantarctic), arctic (antarctic), and polar.
- The Earth’s atmosphere is dominated by nitrogen and oxygen gases. Carbon dioxide and water vapor are only small constituents by volume, but are very important because they absorb longwave radiation and enhance the greenhouse effect.
- Sensible heat and latent heat are additional forms of energy. Sensible heat is contained within a substance. It can be transferred to another substance by conduction or convection. Latent heat is taken up or released when a change of state occurs.
- Part of the solar radiation passing through the atmosphere is absorbed or scattered by molecules, dust, and larger particles. Some of the scattered radiation returns to space as diffuse reflection. The land surfaces, ocean surfaces, and clouds also reflect some solar radiation back to space.
The proportion of radiation that a surface absorbs is termed its **albedo**. The albedo of the Earth and atmosphere as a whole planet is about 30 percent.

The atmosphere absorbs longwave energy emitted by the Earth’s surface, causing the atmosphere to **counterradiate** some of that longwave radiation back to Earth, thereby creating the **greenhouse effect**. Because of this heat trapping, the Earth’s surface temperature is considerably warmer than we might expect for an Earth without an atmosphere.

Flows of energy to and from the Earth–atmosphere system, as well as the atmosphere and surface taken individually, must balance over the long run. Energy flows within the Earth–atmosphere system include shortwave radiation, longwave radiation, sensible heat, and latent heat. Human activities can significantly affect these flows.

**Net radiation** describes the balance between incoming and outgoing radiation. At latitudes lower than 40 degrees, annual net radiation is positive, while it is negative at higher latitudes. This imbalance creates **poleward heat transfer** of latent and sensible heat in the motions of warm water and warm, moist air, which provides the power that drives ocean currents and broad-scale atmospheric circulation patterns.

NASA scientists monitor and map the upward flows of shortwave and longwave radiation over the globe to detect small, long-term changes that could affect global climate.

**KEY TERMS**

- ozone, p. 58
- chlorofluorocarbons (CFCs), p. 58
- energy balance, p. 59
- electromagnetic radiation, p. 59
- absorption, p. 61
- scattering, p. 62
- shortwave radiation, p. 62
- longwave radiation, p. 62
- global radiation balance, p. 63
- insolation, p. 64
- sensible heat, p. 69
- latent heat, p. 70
- albedo, p. 71
- counterradiation, p. 71
- greenhouse effect, p. 71
- net radiation, p. 75
- poleward heat transfer, p. 75

**REVIEW QUESTIONS**

1. What are CFCs, and how do they impact the ozone layer?
2. When and where have ozone reductions been reported? Have corresponding reductions in ultraviolet radiation been noted?
3. What is electromagnetic radiation? How is it characterized? Identify the major regions of the electromagnetic spectrum.
4. How does the temperature of an object influence the nature and amount of electromagnetic radiation that it emits?
5. What is the solar constant? What is its value? What are the units with which it is measured?
6. How does solar radiation received at the top of the atmosphere differ from solar radiation received at the Earth’s surface? What are the roles of absorption and scattering?
7. Compare the terms shortwave radiation and longwave radiation. What are their sources?
8. How does the atmosphere affect the flow of longwave energy from the Earth’s surface to space?
9. What is the Earth’s global energy balance, and how are shortwave and longwave radiation involved?
10. How does the Sun’s path in the sky influence daily insolation at a location? Compare summer solstice and equinox paths of the Sun in the sky for 40° N lat. and the Equator.
11. What influence does latitude have on the annual cycle of daily insolation? on annual insolation?
12. Identify the two largest components of dry air. Why are carbon dioxide and water vapor important atmospheric constituents?
13. Describe latent heat transfer and sensible heat transfer.
14. What is the fate of incoming solar radiation? Discuss scattering and absorption, including the role of clouds.
15. Define albedo and give two examples.
16. Describe the counterradiation process and how it relates to the greenhouse effect.
17. Discuss the energy balance of the Earth’s surface. Identify the types and sources of energy flows that the surface receives, and do the same for energy flows that it loses.
18. Discuss the energy balance of the atmosphere. Identify the types and sources of energy flows that the atmosphere receives, and do the same for energy flows that it loses.
19. What is net radiation? How does it vary with latitude?
**VISUALIZING EXERCISES**

1. Place yourself in Figure 2.8. Imagine that you are standing in the center of the figure where the N–S and E–W lines intersect. Turn so that you face south. Using your arm to point at the Sun’s position, trace the path of the Sun in the sky at the equinox. It will rise exactly to your left, swing upward to about a 50° angle, and then descend to the horizon exactly at your right. Repeat for the summer and winter solstices, using the figure as a guide. Then try it for the North Pole, Equator, and Tropic of Capricorn.

2. Sketch the world latitude zones on a circle representing the globe and give their approximate latitude ranges.

3. Sketch a simple diagram of the Sun above a layer of atmosphere above the Earth’s surface, somewhat like Figure 2.16. Using Figure 2.18 as a guide, draw arrows indicating flows of energy among Sun, atmosphere, and surface. Label each arrow using terms from Figure 2.18.

**ESSAY QUESTIONS**

1. Suppose the Earth’s axis of rotation was perpendicular to the orbital plane instead of tilted at 23½° away from perpendicular. How would global insolation be affected? How would insolation vary with latitude? How would the path of the Sun in the sky change with the seasons?

2. Imagine that you are following a beam of either (a) shortwave solar radiation entering the Earth’s atmosphere heading toward the surface, or (b) a beam of longwave radiation emitted from the surface heading toward space. How will the atmosphere influence the beam?

20. What is the role of poleward heat transport in balancing the net radiation budget by latitude?

21. Using CERES as an example, explain the effect of clouds on shortwave and longwave radiation leaving the Earth-atmosphere system.