What's Happening to Our Weather?

What do skinny polar bears and drowned seal pups, Peruvian malaria epidemics, melting of Mt. Kilimanjaro's famous snows, Chinese drinking-water shortages, unusually severe Bangladeshi floods, coastal erosion in Louisiana, and the disappearance of Edith's Checkerspot butterfly in Southern California have in common? All these phenomena are thought to be signs of human-caused global climate change, which may well be the most critical issue in environmental science today.

The problem is that we are adding greenhouse gases—pollutants that trap in the earth's heat—to the atmosphere at a faster rate than at any time over the past several thousand years. Essentially, we are conducting a giant experiment to see what will happen if we alter atmospheric chemistry. So far, the results don't look very good. All around us, evidence suggests we are modifying our climate on both a local and global scale. The twentieth century was the warmest in the last 1,000 years. The 1990s were the warmest decade and 1998 was the single warmest year of the past millennium.

Polar regions are changing even faster than the rest of the globe. According to Environment Canada, parts of the Arctic coast have warmed as much as 7.5°C (13.5°F) since 1970. Sea ice forms later in the fall and melts earlier in the spring, giving polar bears a shorter seal-hunting season. Hudson's Bay polar bears now weigh as much as 100 kg (220 lbs) less than in the 1960s. In 2002, early melting of ice floes in Canada's Gulf of St. Lawrence appeared to have drowned nearly all of the 200,000 to 300,000 harp seal pups normally born there.

Glaciers are disappearing on every continent. Mt. Kilimanjaro has lost 85 percent of its ice cap since 1915. By 2015, all permanent ice on the mountaintop is expected to be gone. Alpine glaciers feed rivers, such as the Indus, Ganges, Yangtze, Yellow, and Mekong, that supply drinking water and irrigation to more than a billion people in South and East Asia, where water is already becoming a source of conflict. Ocean warming is causing severe storms and heavy monsoon rains that result in flooding in Bangladesh as well as erosion in Louisiana, where rising sea levels have inundated low-lying costal marshes. And Edith's Checkerspot is only one of many species of mammals, birds, amphibians, fish, insects, and plants that are reported to have moved their territory or migration patterns, or to have disappeared altogether as a result of changing climate.

Higher temperatures apparently are allowing disease-causing bacteria, viruses, and fungi to move into new areas where they may harm species as diverse as lions, snails, butterflies, and humans. Climate changes are thought to have contributed to an epidemic of avian malaria that wiped out thousands of birds in Hawaii, the spread of distemper in African lions, and the bleaching of coral reefs around the globe. Unusually warm water off the coast of South America is thought to be responsible for reappearance of cholera in humans during the 1990s after nearly a century of absence.

What do all these changes mean? Taken individually, it's hard to say; they may just be random events in a notoriously variable system. Viewed altogether, however, it seems increasingly evident that we are changing our climate with results we don't yet fully comprehend. Learning something about our atmosphere and how it produces our weather and climate is essential if we are to understand how changing climate might affect us, and what we might do to counter those effects. In this chapter, we'll look at how greenhouse gases and other air pollutants affect human and natural systems, and we'll examine some of the international politics of this crucial topic.

THE ATMOSPHERE AND CLIMATE

We live at the bottom of a virtual ocean of air that extends upward about 500 km (300 mi). In the lowest 10 to 12 km, a layer known as the troposphere, the air moves ceaselessly, flowing and swirling, and continually redistributing heat and moisture from one part of the globe to another. The composition and behavior of the troposphere and other layers control our **weather** (daily temperature and moisture conditions in a place) and our **climate** (long-term weather patterns).

The earth's earliest atmosphere probably consisted mainly of hydrogen and helium. Over billions of years, most of that hydrogen and helium diffused into space. Volcanic emissions added carbon, nitrogen, oxygen, sulfur, and other elements to the atmosphere. Virtually all of the molecular oxygen (O_2) we breathe was probably produced by photosynthesis in blue-green bacteria, algae, and green plants.

Clean, dry air is mostly nitrogen and oxygen (table 9.1). Water vapor concentrations vary from near zero to 4 percent, depending on air temperature and available moisture. Minute particles and liquid droplets—collectively called **aerosols**—also are suspended in the air. Atmospheric aerosols play important roles in the earth's energy budget and in producing rain.

The atmosphere has four distinct zones of contrasting temperature, due to differences in absorption of solar energy (fig. 9.1). The layer of air immediately adjacent to the earth's surface is called the **troposphere** (*tropein* means to turn or change, in Greek). Within the troposphere, air circulates in great vertical and horizontal **convection currents,** constantly redistributing heat and moisture around the globe. The troposphere ranges in depth from about 18 km (11 mi) over the equator to about 8 km (5 mi) over the poles, where air is cold and dense. Because gravity holds most air molecules close to the earth's surface, the troposphere is much more dense than the other layers: it contains about 75 percent of the total

TABLE 9.1 Present Composition of the Lower Atmosphere*

GAS	SYMBOL OR FORMULA	PERCENT BY VOLUME
Nitrogen	N_2	78.08
Oxygen	O_2	20.94
Argon	Ar	0.934
Carbon dioxide	CO_2	0.035
Neon	Ne	0.00182
Helium	He	0.00052
Methane	CH_4	0.00015
Krypton	Kr	0.00011
Hydrogen	H_2	0.00005
Nitrous oxide	N_2O	0.00005
Xenon	Xe	0.000009

*Average composition of dry, clean air.

mass of the atmosphere. Air temperature drops rapidly with increasing altitude in this layer, reaching about –60ºC (–76ºF) at the top of the troposphere. A sudden reversal of this temperature gradient creates a sharp boundary called the tropopause, which limits mixing between the troposphere and upper zones.

The **stratosphere** extends from the tropopause up to about 50 km (31 mi). It is vastly more dilute than the troposphere, but it has similar composition—except that it has almost no water vapor and nearly 1,000 times more **ozone** (O_3). This ozone absorbs some wavelengths of ultraviolet solar radiation, known as UV-B (290–330 nm, see fig. 2.9). This absorbed energy makes the atmosphere warmer toward the top of the stratosphere. Since UV radiation damages living tissues, this UV absorption in the stratosphere also protects life on the surface. Recently discovered depletion of stratospheric ozone, especially over Antarctica, is allowing increased amounts of UV radiation to reach the earth's surface. If observed trends continue, this radiation could cause higher rates of skin cancer, genetic mutations, crop failures, and disruption of important biological communities, as you will see later in this chapter.

Unlike the troposphere, the stratosphere is relatively calm. There is so little mixing in the stratosphere that volcanic ash or human-caused contaminants can remain in suspension there for many years.

Above the stratosphere, the temperature diminishes again, creating the mesosphere, or middle layer. The thermosphere (heated layer) begins at about 50 km. This is a region of highly ionized (electrically charged) gases, heated by a steady flow of high-energy solar and cosmic radiation. In the lower part of the thermosphere, intense pulses of high-energy radiation cause electrically charged particles (ions) to glow. This phenomenon is what we know as the *aurora borealis* and *aurora australis*, or northern and southern lights.

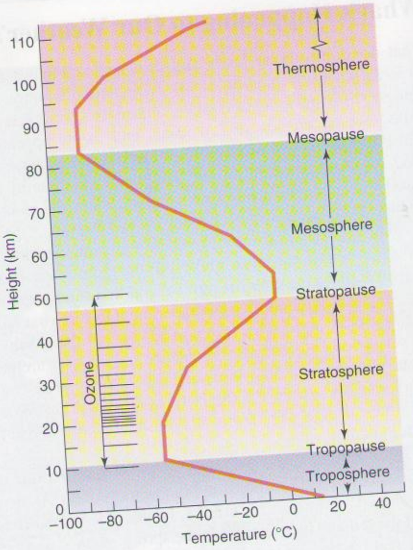

FIGURE 9.1 *Temperatures change drastically in the four layers the atmosphere. Bars in the ozone graph represent relative concentrations of stratospheric ozone with altitude.*
Source: Courtesy of Dr. William Culver, St. Petersburg Junior College.

No sharp boundary marks the end of the atmosphere. Pr sure and density decrease with distance from the earth until t become indistinguishable from the near vacuum of interste space.

Energy and the "Greenhouse Effect"

The sun supplies the earth with an enormous amount of en but that energy is not evenly distributed over the globe. Inco solar radiation (insolation) is much stronger near the equator at high latitudes. Of the solar energy that reaches the outer at phere, about one-quarter is reflected by clouds and atmosp gases, and another quarter is absorbed by carbon dioxide, vapor, ozone, methane, and a few other gases (fig. 9.2). energy absorption warms the atmosphere slightly. About h incoming solar radiation (insolation) reaches the earth's su Most of this energy is in the form of light or infrared (heat) (see fig. 2.10). Some of this energy is reflected by bright su such as snow, ice, and sand. The rest is absorbed by the earth face and by water. Surfaces that *reflect* energy have a high (reflectivity). Most of these surfaces appear bright to us b they reflect light as well as other forms of radiative energ faces that *absorb* energy have a low albedo and generally dark. Black soil, asphalt pavement, and dark green vegetat example, have low albedos (table 9.2).

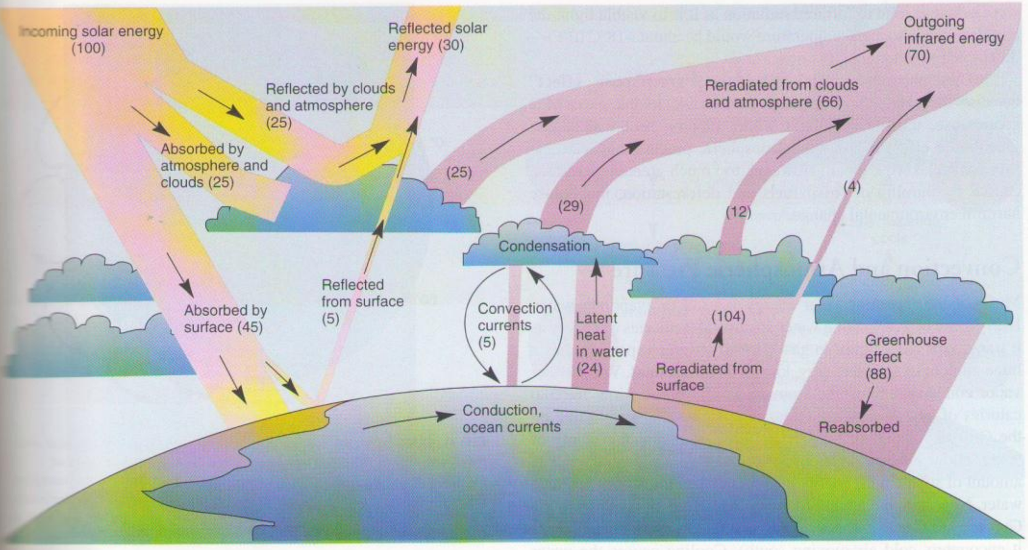

FIGURE 9.2 *Energy balance between incoming and outgoing radiation. The atmosphere absorbs or reflects about half of the solar energy reaching the earth. Most of the energy reemitted from the earth's surface is long-wave, infrared energy. Most of this infrared energy is absorbed by aerosols and gases in the atmosphere and is reradiated toward the planet, keeping the surface much warmer than it would otherwise be. This is known as the greenhouse effect. The numbers shown are arbitrary units. Note that for 100 units of incoming solar energy, 100 units are reradiated to space, but more than 100 units are radiated from the earth's surface because of the greenhouse effect.*

TABLE 9.2 Albedo (Reflectivity) of Surfaces

SURFACE	ALBEDO (%)
Fresh snow	80–85
Dense clouds	70–90
Water (low sun)	50–80
Sand	20–30
Water (sun overhead)	5
Forest	5–10
Black soil	3
Earth/atmosphere average	30

Absorbed energy heats the absorbing surface (such as an asphalt parking lot in summer), evaporates water, or provides the energy for photosynthesis in plants. Following the second law of thermodynamics, absorbed energy is gradually reemitted as lower-quality heat energy. A brick building, for example, absorbs energy in the form of light and reemits that energy in the form of heat.

The change in energy quality is very important because the atmosphere selectively absorbs longer wavelengths. Most solar energy comes in the form of intense, high-energy light or near-infrared wavelengths (fig. 2.10). This short-wavelength energy passes relatively easily through the atmosphere to reach the earth's surface. Energy re-released from the earth's warmed surface ("terrestrial energy") is lower-intensity, longer-wavelength energy in the far-infrared part of the spectrum. Atmospheric gases, especially carbon dioxide and water vapor, absorb much of this long-wavelength energy, re-releasing it in the lower atmosphere and letting it leak out to space only slowly. This terrestrial energy provides most of the heat in the lower atmosphere. If the atmosphere

APPLICATION: How Much Heat Is Released in a 1-in. Rainstorm in Your Neighborhood?

Most Americans measure rainfall in inches, but centimeters are easier to calculate. A 1-in. rainfall is about 2.54 cm of rain. Suppose your neighborhood is a 1 km × 1 km square. If rain releases 580 cal/cm^3, how much heat is released by this rainstorm?

Answer: $\frac{25.4\text{ cm of rain}}{1} \times \frac{100{,}000\text{ cm}}{\text{km}} \times \frac{100{,}000\text{ cm}}{\text{km}} \times \frac{580\text{ cal}}{\text{cm}^3\text{ of rain}} = 17.2 \times 10^{12}\text{ cal.}$

were as transparent to infrared radiation as it is to visible light, the earth's average surface temperature would be about –18°C (0°F)—33°C (59°F) colder than it is now.

This phenomenon is called the **"greenhouse effect"** because the atmosphere, loosely comparable to the glass of a greenhouse, transmits sunlight while trapping heat inside. The greenhouse effect is a natural atmospheric process that is necessary for life as we know it. However, too much greenhouse effect, caused by burning of fossil fuels and deforestation, may cause harmful environmental change.

Convection and Atmospheric Pressure

Much of the incoming solar energy is used to evaporate water. Every gram of evaporating water absorbs 580 calories of energy as it transforms from liquid to gas. Globally, water vapor contains a huge amount of stored energy, known as **latent heat**. When water vapor condenses, returning from a gas to a liquid form, the 580 calories of heat energy are released. Imagine the sun shining on the Gulf of Mexico in the winter. Warm sunshine and plenty of water allow continuous evaporation that converts an immense amount of solar (light) energy into latent heat stored in evaporated water. Now imagine a wind blowing the humid air north from the Gulf toward Canada. The air cools as it moves north (especially if it encounters cold air moving south). Cooling causes the water vapor to condense. Rain (or snow) falls as a consequence. Note that it is not only water that has moved from the Gulf to the Midwest: 580 calories of heat have also moved with every gram of moisture. The heat and water have moved from a place with strong incoming solar energy to a place with much less solar energy and much less water. The redistribution of heat and water around the globe are essential to life on earth.

Uneven heating, with warm air close to the equator and colder air at high latitudes, also produces pressure differences that cause wind, rain, storms, and everything else we know as weather. As the sun warms the earth's surface, the air nearest the surface warms and expands, becoming less dense than the air above it. The warm air must then rise above the denser air. Vertical convection currents result, which circulate air from warm latitudes to cool latitudes and vice versa. These convection currents can be as small and as localized as a narrow column of hot air rising over a sun-heated rock, or they can cover huge regions of the earth. At the largest scale, the convection cells are described by a simplified model known as Hadley cells, which redistribute heat globally (fig. 9.3).

Where air rises in convection currents, air pressure at the surface is low. Where air is sinking, or subsiding, air pressure is high. On a weather map these high and low pressure centers, or rising and sinking currents of air, move across continents. In most of North America, they generally move from west to east. Rising air tends to cool with altitude, releasing latent heat that causes further rising. Very warm and humid air can rise very vigorously, especially if it is rising over a mass of very cold air. Storms associated with low pressure and rising air are known as cyclonic storms. These include some of the most violent storms we know: hurricanes, tornadoes, and intense rain and hail are forms of cyclonic storms (fig. 9.4).

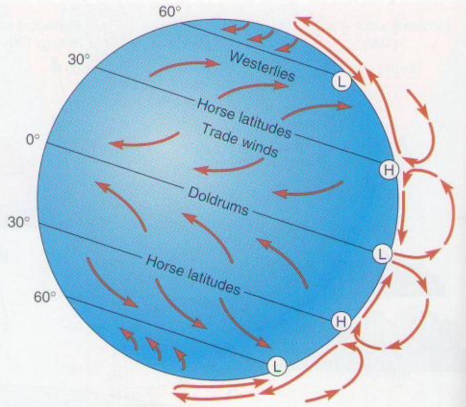

FIGURE 9.3 *General circulation patterns redistribute heat and moisture around the globe. The approximate locations of vertical convection currents, generally referred to as Hadley cells, are noted on the right side. Low pressure belts (L) occur at latitudes where air rises. High pressure belts (H) occur where air sinks. Dominant winds, such as trade winds and westerlies, also occur in latitudinal bands.*

Pressure differences are an important cause of wind. There is always someplace with sinking (high pressure) air and someplace with low pressure (rising) air. Air moves from high-pressure centers toward low-pressure areas, and we call this movement wind.

Why Does It Rain?

To understand why it rains, remember two things: water condenses as air cools, and air cools as it rises. Any time air is rising, clouds, rain, or snow might form. Cooling occurs because of changes in pressure with altitude: air cools as it rises (as pressure decreases); air warms as it sinks (as pressure increases). Air rises in convection currents where solar heating is intense, such as over the equator. Moving masses of air also rise over each other and cool. Air also rises when it encounters mountains. If the air is moist (if it has recently come from over an ocean or an evaporating forest region, for example), condensation and rainfall are likely as the air is lifted (fig. 9.5). Regions with intense solar heating, frequent colliding air masses, or mountains tend to receive a great deal of precipitation.

Where air is sinking, on the other hand, it tends to warm because of increasing pressure. As it warms, available moisture evaporates. Rainfall occurs relatively rarely in areas of high pressure. High pressure and clear, dry conditions occur where convection currents are sinking. High pressure also occurs where air sinks after flowing over mountains. Figure 9.3 shows sinking, dry air at about 30° north and south latitudes. If you look at a world map, you will see a band of deserts at approximately these latitudes.

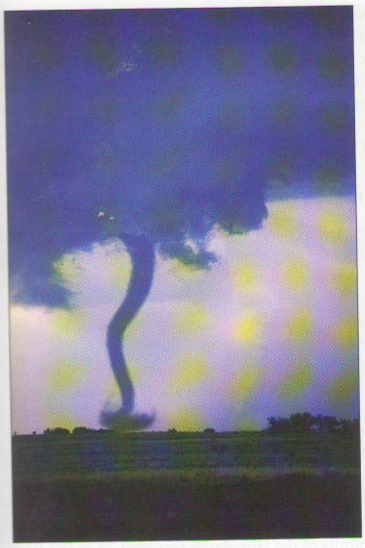

FIGURE 9.4 *Tornadoes are local cyclonic storms caused by rapid mixing of cold, dry air and warm, wet air. Wind speeds in the swirling funnel can reach 320 km/hr (200 mph).*

Another ingredient is usually necessary to initiate condensation of water vapor: condensation nuclei. Tiny particles of smoke, dust, sea salts, spores, and volcanic ash all act as condensation nuclei. These particles form a surface on which water molecules can begin to coalesce. Without them even supercooled vapor can remain in gaseous form. Even apparently clear air can contain large numbers of these particles, which are generally too small to be seen by the naked eye.

The Coriolis Effect and Jet Streams

Large-scale winds tend not to move in a straight line across the earth's surface. In the Northern Hemisphere, they generally bend clockwise (right), and in the Southern Hemisphere, they bend counterclockwise (left). This curving pattern results from the fact that the earth rotates in an eastward direction as the winds move above the surface. The apparent curvature of the winds is known as the **Coriolis effect.** On a global scale, this effect produces steady, reliable wind patterns, such as the trade winds and the midlatitude Westerlies (see fig. 9.3). Ocean currents similarly curve clockwise in the Northern Hemisphere and counterclockwise in the south (see appendix 4, p. 376). On a regional scale, the Coriolis effect produces cyclonic winds, or wind movements controlled by the earth's spin. Cyclonic winds spiral clockwise out of an area of high pressure in the Northern Hemisphere and counterclockwise into a low-pressure zone. If you look at a weather map in the newspaper, can you find this counterclockwise spiral pattern?

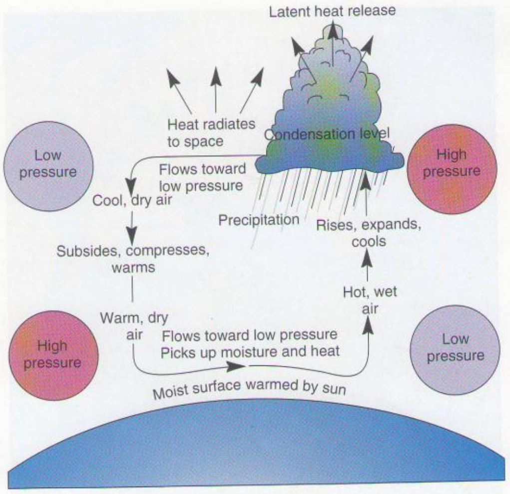

FIGURE 9.5 *Convection currents and latent energy cause atmospheric circulation and redistribution of heat and water around the globe.*

Why does this curving or spiraling motion occur? Imagine you were looking down on the North Pole of the rotating earth. Now imagine that the earth was a merry-go-round in a playground, with the North Pole at its center and the equator around the edge. As it spins counter-clockwise (eastward), the spinning edge moves very fast (a full rotation, 39,800 km, every 24 hours for the real earth, or more than 1,600 km/hour!). Near the center, though, there is very little eastward velocity. If you threw a ball from the edge toward the center, it would be traveling faster (edge speed) than the middle. It would appear, to someone standing on the merry-go-round, to curve toward the right. If you threw the ball from the center toward the edge, it would start out with no eastward velocity, but the surface below it would spin eastward, making the ball end up, to a person on the merry-go-round, west of its starting point. Winds move above the earth's surface much as the ball does. If you were looking down at the South Pole, you would see the earth spinning clockwise, and winds—or thrown balls—would appear to bend left. Incidentally, this effect does not apply to drains in your house. Their movement is far too small to be affected by the spinning of the earth.

At the top of the troposphere are **jet streams,** hurricane-force winds that circle the earth. These powerful winds follow an undulating path approximately where the vertical convection currents known as the Hadley and Ferrell cells meet. The approximate path of one jet stream over the Northern Hemisphere is shown in fig. 9.6. Although we can't perceive jet streams on the ground, they are