CHAPTER 15

Arctic sea ice is disappearing at an accelerating rate. The 2008 summer extent shown here was the lowest on record at the time.

Air, Weather, and Climate

Learning Outcomes

After studying this chapter, you should be able to:

15.1 Describe the general composition and structure of the atmosphere.
15.2 Explain why weather events follow general patterns.
15.3 Outline some factors in natural climate variability.
15.4 Explain how we know recent climate change is human-caused.
15.5 List some effects of climate change.
15.6 Identify some solutions being developed to slow climate change.

"I was born in 1992. You have been negotiating all my life. You cannot tell me you need more time."

~ Christina Ora, youth delegate from the Solomon Islands addressing the plenary at COP15, 2009

Case Study When Wedges Do More Than Silver Bullets

In the summer of 2010, Russians suffered the worst heat wave in 1,000 years of recorded Russian history. In Moscow, temperatures exceeded 100°F (40°C) for the first time in history, and the death rate doubled, from heatstroke and lung ailments caused by smoke from burning forests and peat swamps. Heat and smoke were blamed for 11,000 extra deaths that August. More than seven weeks of extreme temperatures also destroyed one-third of Russian grain crops, and wheat prices doubled worldwide. Extreme conditions can happen in a complex climate system, but these were consistent with the increasingly volatile weather expected by climate scientists, as increasing concentrations of "greenhouse gases" (fig. 15.1) retain more and more energy in our atmosphere.

Global average temperatures are about 1°C (about 2°F) higher than they've been in centuries This difference might seem slight, but the difference between the last glacial maximum and today is only about 5°C. A change of 1°C allows new crop pests and weeds to survive winters farther north. Even moderate warming can dry soil enough to force farmers to irrigate crops more, where irrigation is possible, or to abandon farms in poor countries and move to already-overstressed cities.

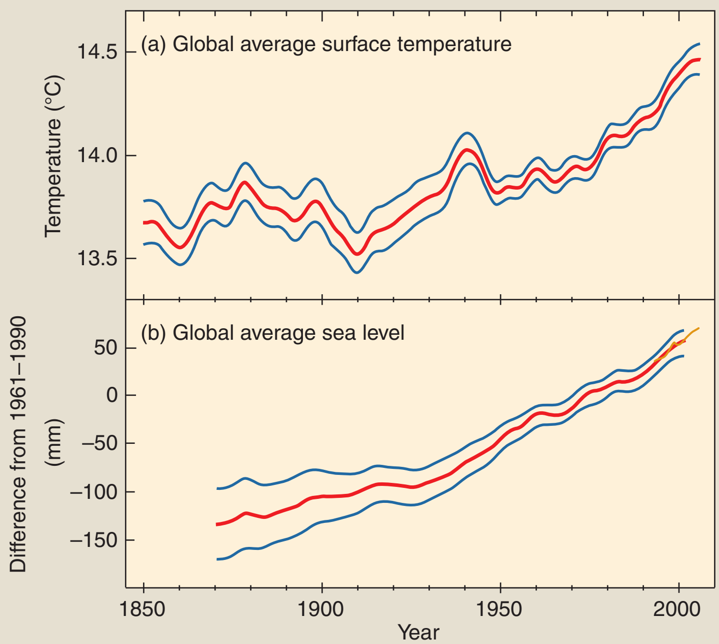


FIGURE 15.1 Observed temperatures have increased in recent decades. Blue lines show uncertainty (range of possible values) for global averages (red lines). **Source:** IPCC, 2007.

In California and other parts of the western United States, cities rely on snowmelt in the mountains for water. Here the specter of declining snowpack is sobering up voters and politicians alike. But still we have a hard time getting around to finding policies to reduce greenhouse gas emissions.

Meanwhile, data indicate that if we don't reduce our carbon output in the next few years, we will permanently lose the ice caps and permafrost, which help moderate the global climate. Soon we will be on a path for irreversible and unavoidable increases of 5–7°C within the coming century, with sea-level rises of 1 m or more by 2100.

Among climate scientists who study the data, there is no longer any debate about whether our carbon emissions are triggering climate change or whether that change is likely to be extraordinarily costly, in both human and economic terms. Remaining debates are only about details: how fast sea levels are likely to rise, or where drought will be worst, or about fine-tuning of climate models.

Among policymakers, it's another matter. Politicians are responsible for establishing new rules to reduce our carbon output, but many still have a hard time understanding the connection between climate change and the increasing incidence of forest fires, drought, water shortages, heat waves, and pest outbreaks. Energy-industry money also pays liberally to sow doubt in the minds of policymakers and the public. Climate changes are gradual, proceeding over decades, so it's hard to get the public focused on remedies today.

Many politicians have hoped for a silver bullet—a technology that will fix the problem all at once—perhaps nuclear fusion, or space-based solar energy, or giant mirrors that would reflect solar energy away from the earth's surface. While these are intriguing ideas, none are workable now, and climate scientists are warning us that immediate action is critical to avoid tipping points such as the loss of polar ice, ancient arctic permafrost, and glaciers.

Wedges Can Work Now

To help us out of this quagmire of indecision, a Princeton ecologist and an engineer have proposed a completely different approach to imagining alternatives. Their approach has come to be called **wedge analysis,** or breaking down a large problem into smaller, bite-size pieces. By calculating the contribution of each wedge, we can add them up, see the magnitude of their collective effect, and decide that it's worth trying to move forward.

Stephen Pacala and Robert Socolow, of Princeton University's Climate Mitigation Initiative, introduced the wedge idea in a 2004 article in the journal *Science*. Their core idea was that currently available technologies—efficient vehicles, buildings, power plants, alternative fuels—could solve our problems today, if we just take them seriously. Future technologies, no matter how brilliant, can do nothing for us right now. Pacala and Socolow have further honed their ideas in subsequent papers, and others have picked up the wedge idea to envision strategies for problems such as reducing transportation energy use or water consumption. The *Science* paper focuses on CO_2 production, but the authors point out that similar analysis could be done for other greenhouse gases.

Pacala and Socolow described three possible trajectories in our carbon emissions. The "business as usual" scenario follows

Case Study continued

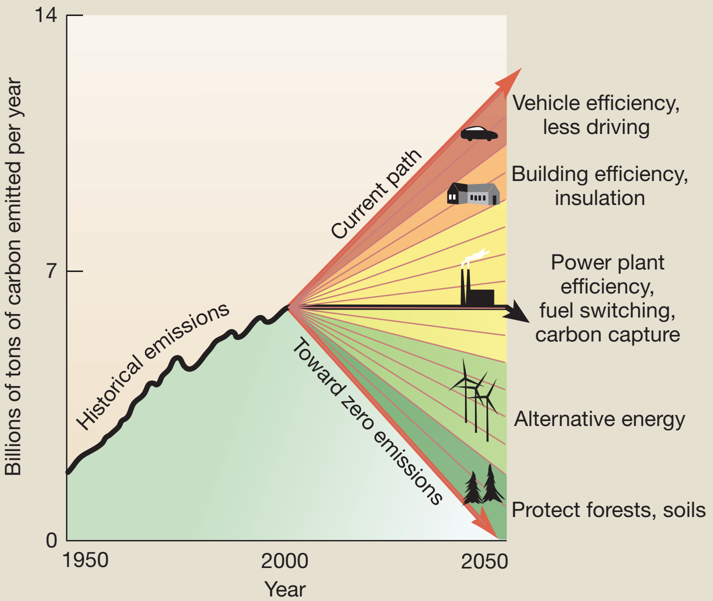


FIGURE 15.2 We could stabilize or even reduce carbon emissions now if we focus on multiple modest strategies.

the current pattern of constantly increasing CO_2 output. This trajectory heads toward at tripling of CO_2 by 2100, accompanied by temperature increases of around 5°C (9°F) and a sea-level rise of 0.5–1 m (fig. 15.2).

A second trajectory is a "stabilization scenario." In this scenario, we prevent further increases in CO_2 emissions, and we nearly double CO_2 in the atmosphere by 2100. Temperatures increase by about 2–3°C, and sea level rises by about 29–50 cm.

A third trajectory, declining CO_2 emissions, could result from new energy sources and better land management.

To achieve stabilization, we need to reduce our annual carbon emissions by about 7 billion tons (or 7 gigatons, GT) per year within 50 years (fig. 15.2). This 7 GT can be subdivided into seven wedges, each representing 1 GT of carbon we need to cut.

Cutting one of those gigatons could be accomplished by increasing fuel economy in our cars from 30 to 60 mpg. Another gigaton could be eliminated if we reduced reliance on cars (with more public transit or less suburban sprawl, for example) and cut driving from an average 10,000 miles to 5,000 miles per year. Better insulation and efficient appliances in our houses and office buildings would equal another wedge. Increased efficiency in our coal power plants would equal another wedge.

These steps add up to 4/7 of the stabilization triangle, using currently available technologies. The remaining 3/7 can be accomplished by capturing and storing carbon at power plants, by changing the way power plants operate, and by reducing reliance on coal power. Another set of seven wedges, including alternative energy, preventing deforestation, and reducing soil loss, could put us on a trajectory to reduce our CO_2 emissions and prevent disastrous rates of climate change. Further details on the wedges are given later in this chapter.

These strategies also offer economic advantages. Improved efficiency and reduced energy consumption mean long-term cost savings. Efficient cars will cut household expenses. Sustainable infrastructure can provide long-term employment stability, rather than the boom-and-bust cycles of coal and oil extraction. We continually replace buildings, roads, and vehicles; if we start now to build them better, we could drastically cut our costs in the near future.

Cleaner power sources will also reduce asthma and other respiratory illnesses, saving health care costs and improving quality of life. Less reliance on coal will reduce toxic mercury in our food, since coal power plants are the main source of airborne mercury, which enters our food chain through aquatic ecosystems and the fish we eat. Better land management can preserve food, water, and wood resources for the future.

Perhaps it's not surprising, then, that thousands of local communities are stepping up to lead the way on these initiatives, even while national governments dither. You don't have to care about climate change to agree about saving money and reducing smog. If you do care about climate change, it feels good to stop fretting and start acting.

In this chapter we'll examine the composition and behavior of our atmosphere and the factors that make it change over time. For related resources, including Google Earth™ placemarks that show locations where these issues can be seen, visit EnvironmentalScience-Cunningham.blogspot.com.

Further Reading:

Pacala, S., and Socolow, R. 2004. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science,* 305 (5686): 968–72.

15.1 What is the Atmosphere?

Of all the planets in our solar system, only the earth has an atmosphere that makes life possible. The atmosphere retains solar heat, protects us from deadly radiation in space, and distributes the water that makes up most of your body. The atmosphere consists of gas molecules, held near the earth's surface by gravity and extending upward about 500 km. All the weather we see is in just the lowest 10–12 km, in a constantly circulating and swirling layer known as the troposphere. **Weather** is a term for the short-lived and local patterns of temperature and moisture that result from this circulation. In contrast, **climate** is long-term patterns of temperature and precipitation. Understanding the difference between short-term variations and long-term patterns is important in understanding our climate.

The earth's earliest atmosphere probably consisted mainly of lightweight 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 the molecular oxygen (O_2) that we breathe was probably produced by photosynthesis in blue-green bacteria, algae, and green plants.

Clean, dry air is mostly nitrogen and oxygen (table 15.1). 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 (fig. 15.3). Atmospheric aerosols are important in capturing, distributing, or reflecting energy.

The atmosphere has four distinct zones of contrasting temperature, which result from differences in absorption of solar energy (fig. 15.4). 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 absorbs energy from the sun-warmed earth's surface, and from moisture evaporating from oceans. Warmed air circulates in great vertical and horizontal **convection currents,** which occur when warm, low-density air rises above a cooler, denser layer. (You can observe a similar process in a pot of simmering water on the stove: water heated at the hot bottom of the pot rises up above the cooler layers at the top, creating convective circulation patterns.) Convection constantly redistributes heat and moisture around the globe. The depth of the troposphere ranges from about 18 km (11 mi) over the equator, where heating and convection are intense, to about 8 km (5 mi) over the poles, where air is cold and dense. The troposphere consists mainly of relatively large, heavy molecules, held close to the

Table 15.1 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.

FIGURE 15.3 The atmospheric processes that purify and redistribute water, moderate temperatures, and balance the chemical composition of the air are essential in making life possible. To a large extent, living organisms have created, and help to maintain, the atmosphere on which we all depend.

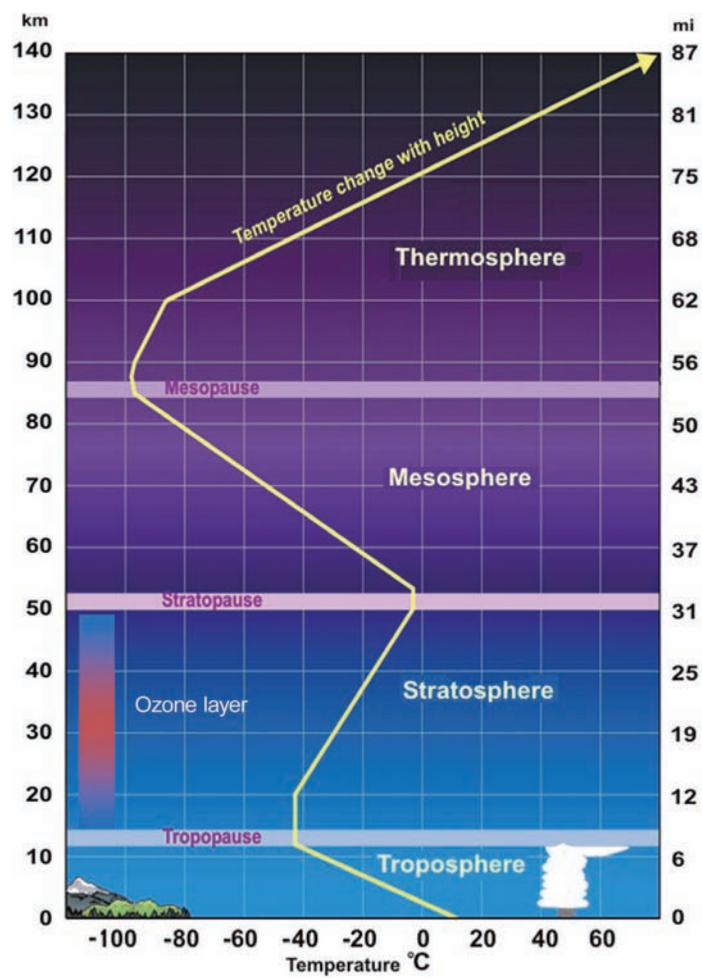


FIGURE 15.4 Layers of the atmosphere vary in temperature and composition. Most weather happens in the troposphere. Stratospheric ozone is important for blocking ultraviolet solar energy.

earth's surface by gravity. Consequently, the troposphere contains about 75 percent of the total mass of the atmosphere. Within the troposphere, temperatures drop rapidly with increasing distance from the earth, reaching about −60°C (−76°F). At this point air is no longer warmer than its surroundings, and it ceases to rise. We call this boundary, where mixing ends, the tropopause.

The **stratosphere** extends from the tropopause up to about 50 km (31 mi). This layer 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). Near the earth's surface ozone is a pollutant, but in the stratosphere it serves a very important function: Ozone absorbs certain wavelengths of ultraviolet solar radiation, known as UV-B (290–330 nm; see fig. 3.10). This absorbed energy warms the stratosphere, and temperature increases with elevation. Stratospheric UV absorption also protects life on the earth's surface, because UV radiation damages living tissues, causing skin cancer, genetic mutations, and crop failures. A number of air pollutants, including Freon, once used in refrigerators, and bromine compounds, used as pesticides, deplete stratospheric ozone, especially over Antarctica. This has allowed increased amounts of UV radiation to reach the earth's surface (see fig. 16.14).

Unlike the troposphere, the stratosphere is relatively calm, because warm layers lie above colder layers. There is so little mixing that when volcanic ash or human-caused contaminants reach the stratosphere, they can remain in suspension there for years.

Above the stratosphere, the temperature diminishes again in the mesosphere, or middle layer. The thermosphere (heated layer) begins at about 80 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. We call this phenomenon the *aurora borealis* and *aurora australis,* or northern and southern lights.

No sharp boundary marks the end of the atmosphere. The density of gas molecules decreases with distance from the earth until it becomes indistinguishable from the near-vacuum of interstellar space.

Absorbed solar energy warms our world

The sun supplies the earth with an enormous amount of energy, but that energy is not evenly distributed over the globe. Incoming solar radiation (insolation) is much stronger near the equator than at high latitudes. Of the solar energy that reaches the outer atmosphere, about one-quarter is reflected by clouds and atmospheric gases, and another quarter is absorbed by carbon dioxide, water vapor, ozone, methane, and a few other gases (fig. 15.5). This energy absorption

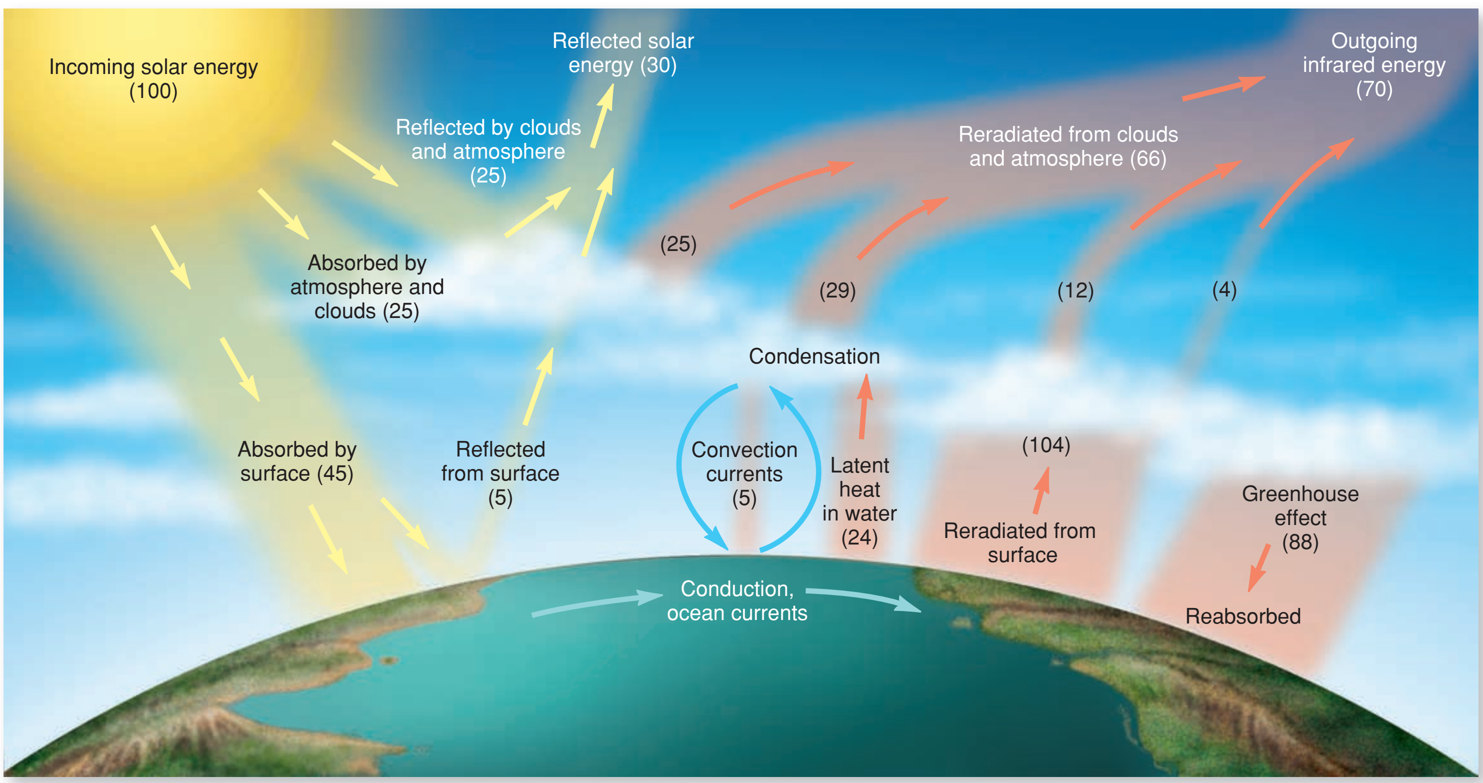


FIGURE 15.5 Energy balance between incoming and outgoing radiation. The atmosphere absorbs or reflects about half of the solar energy reaching the earth. Most of the energy reemitted from the earth's surface is long-wave, infrared energy. Most of this infrared energy is absorbed by aerosols and gases in the atmosphere and is re-radiated toward the planet, keeping the surface much warmer than it would otherwise be. This is known as the greenhouse effect.

Table 15.2 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

warms the atmosphere. About half of incoming energy reaches the earth's surface. Some of this energy is reflected by bright surfaces, such as snow and ice. The rest is absorbed by the earth's surface and by water. Surfaces that *reflect* energy have a high **albedo** (reflectivity). Most of these surfaces appear bright to us because they reflect light as well as other forms of radiative energy. Surfaces that *absorb* energy have a low albedo and generally appear dark. Black soil, pavement, and open water, for example, have low albedos (table 15.2).

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.

Water is extremely efficient at absorbing and storing energy. This is why increasing open water at the poles (shown in this chapter's opening photo) worries climatologists. For hundreds of thousands of years, the Arctic has been mostly white, reflecting most energy that reached the icy surface. Now open water increasingly captures and stores that energy, further accelerating ice melting and atmospheric warming. This is a good example of a **positive feedback loop,** in which melting leads to further melting, with probably dramatic consequences.

The greenhouse effect is energy capture by gases in the atmosphere

The change in energy quality shown in fig. 15.5 is important because the atmosphere selectively absorbs longer wavelengths. Most solar energy comes in the form of intense, high-energy light or near-infrared wavelengths (see fig. 3.10), which pass 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 radiation in the far-infrared part of the spectrum. Atmospheric gases, especially carbon dioxide and water vapor, absorb much of this long-wavelength energy and re-release it in the lower atmosphere. This long-wave terrestrial energy provides most of the heat in the lower atmosphere (see red shading in fig. 15.5). If the atmosphere were as transparent to infrared radiation as it is to visible light, the earth's average surface temperature would be about 18°C (33°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 strong a greenhouse effect, caused by burning of fossil fuels and deforestation, can destabilize the environment we're used to. We will discuss this issue later in this chapter.

Greenhouse gases is a general term for gases that are especially effective at capturing the long-wavelength energy from the earth's surface. Water vapor (H_2O) is the most abundant greenhouse gas, and it is always present in the atmosphere. Carbon dioxide (CO_2) is the most abundant human-caused greenhouse gas, followed by methane (CH_4), nitrous oxide (N_2O), and dozens of other gases. These are discussed later in this chapter.

Evaporated water stores energy, and winds redistribute it

Much of the incoming solar energy is used to evaporate water. In fact, 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 rises and moves north. Cooling causes the water vapor to condense. Rain (or snow) falls as a consequence.

Note that not only water 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 is essential to life on earth. Without oceans to absorb and store heat, and wind currents to redistribute that heat in the latent energy of water vapor, the earth would undergo extreme temperature fluctuations like those of the moon, where it is 100°C (212°F) during the day and −130°C (−200°F) at night. Water performs this vital function because of its unique properties in heat absorption and energy of vaporization (chapter 3).

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 noted earlier, air circulation occurs as the sun warms the earth's surface, and air nearest the surface warms and expands, becoming less dense than the air above it. Rising warm air produces vertical convection currents. 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,

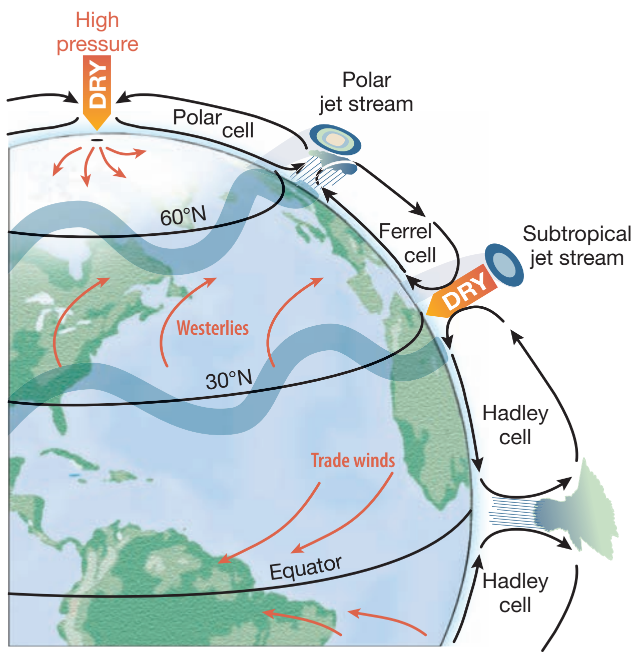


FIGURE 15.6 Convection cells circulate air, moisture, and heat around the globe. Jet streams develop where cells meet, and surface winds result from convection. Convection cells expand and shift seasonally.

circulating air from warm latitudes to cool latitudes and back. At the largest scale, the convection cells are described by a simplified model known as Hadley cells, which redistribute heat globally (fig. 15.6).

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, which causes further rising. Very warm and humid air can rise very vigorously, especially if it is rising over a mass of very cold air. As water vapor carried aloft cools and condenses, it releases energy that fuels violent storms, which we will discuss later.

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

15.2 Weather Has Regional Patterns

Weather involves the physical conditions in the atmosphere (humidity, temperature, air pressure, wind, and precipitation) over short time scales, usually days or weeks. In this section we'll examine why those patterns occur. In general, most major weather patterns result from uneven solar heating, which causes areas of high and low pressure, together with spinning of the earth.

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. 15.7). 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 15.6 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.

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.

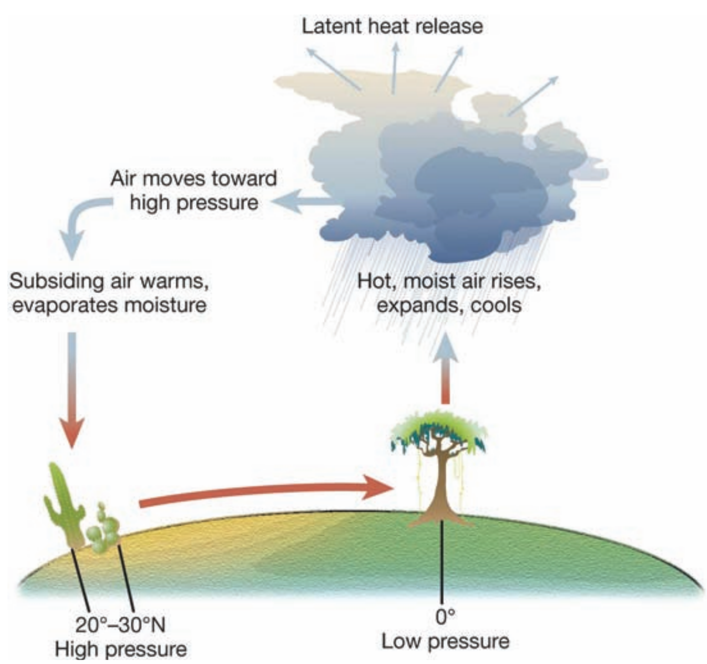


FIGURE 15.7 Convection currents distribute latent energy (heat in evaporated water) around the globe.

The Coriolis effect explains why winds seem to curve

In the Northern Hemisphere, winds generally appear to bend clockwise (right), and in the Southern Hemisphere they appear to bend counterclockwise (left). Examples include the trade winds that brought Columbus to the Americas and the midlatitude Westerlies that bring hurricanes north from Florida to North Carolina (see fig. 15.6). Ocean currents similarly curve clockwise in the Northern Hemisphere (the Gulf Stream) and counterclockwise in the south (the Humboldt Current near Peru). 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 predictable wind patterns and currents. 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, you can probably find this spiral pattern.

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 counterclockwise (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, because the distance around a circle near the pole is relatively short. If you were standing on the edge of the merry-go-round and threw a ball toward the center, the ball would be traveling eastward very fast, at the speed of the spinning edge, as well as toward the center. To someone standing on the merry-go-round, the ball would appear to be traveling east as well as north, making a 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. 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.

Winds move above the earth's surface much as the ball does. However, it's a myth that bathtubs and sinks spiral in opposite directions in the Northern and Southern Hemispheres. Those movements are 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 figure 15.8. Although we can't perceive jet streams on the ground, they are important to us because they greatly affect weather patterns. Sometimes jet streams dip down near the top of the world's highest mountains, exposing mountain climbers to violent, brutally cold winds.

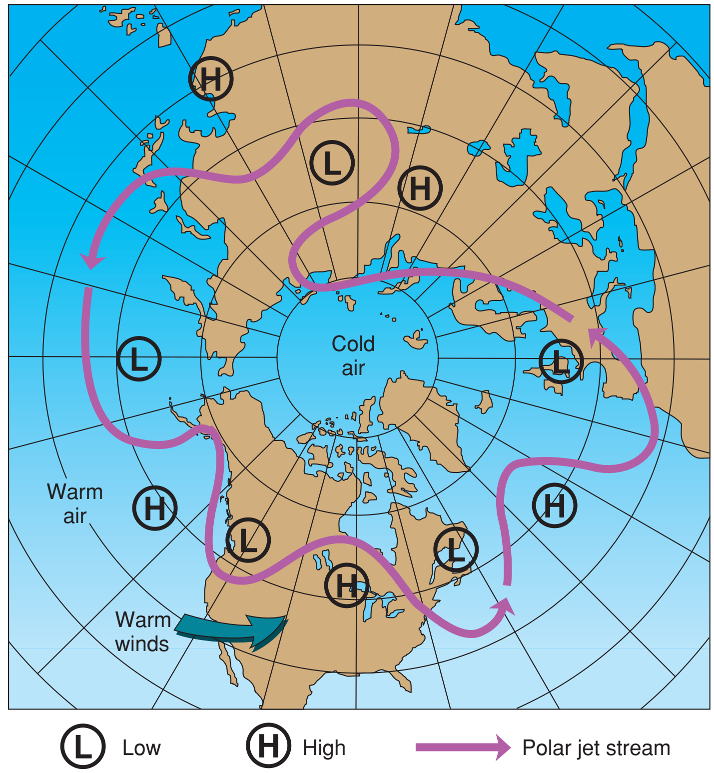


FIGURE 15.8 A typical pattern of the arctic circumpolar vortex. This large, circulating mass of cold air sends "fingers," or lobes, across North America and Eurasia, spreading storms in their path. If the vortex becomes stalled, weather patterns stabilize, causing droughts in some areas and excess rain elsewhere.

Ocean currents modify our weather

Warm and cold ocean currents strongly influence climate conditions on land. Surface ocean currents result from wind pushing on the ocean surface, as well as from the Coriolis effect. As surface water moves, deep water wells up to replace it, creating deeper ocean currents. Differences in water density—depending on the temperature and saltiness of the water—also drive ocean circulation. Huge cycling currents called gyres carry water north and south, redistributing heat from low latitudes to high latitudes (see fig. 17.4). The Alaska current, flowing from Alaska southward to California, keeps San Francisco cool and foggy during the summer.

The Gulf Stream, one of the best-known currents, carries warm Caribbean water north past Canada's maritime provinces to northern Europe. This current is immense, some 800 times the volume of the Amazon, the world's largest river. The heat transported from the Gulf keeps Europe much warmer than it should be for its latitude. As the warm Gulf Stream passes Scandinavia and swirls around Iceland, the water cools and evaporates, becomes dense and salty, and plunges downward, creating a strong, deep, southward current. Oceanographer Wallace Broecker calls this the ocean conveyor system (see fig. 17.4).

Ocean circulation patterns were long thought to be unchanging, but now oceanographers believe that currents can shift abruptly. About 11,000 years ago, for example, as the earth was gradually warming at the end of the Pleistocene ice age, a huge body of meltwater, called Lake Agassiz, collected along the south margin of the North American ice sheet. At its peak it contained more water than all the current freshwater lakes in the world. Drainage of this lake to the east was blocked by ice covering what is now the Great Lakes. When that ice dam suddenly gave way, it's estimated that some 163,000 km^3 of fresh water roared down the St. Lawrence Seaway and out into the North Atlantic, where it layered on top of the ocean and prevented the sinking of deep, cold, dense seawater. This, in turn, apparently stopped the oceanic conveyor and plunged the whole planet back into an ice age (called the Younger Dryas after a small tundra flower that became more common in colder conditions) that lasted for another 1,300 years.

Could this happen again? Meltwater from Greenland glaciers is now flooding into the North Atlantic just where the Gulf Stream sinks and creates the deep south-flowing current. Already, evidence shows that the deep return flow has weakened by about 30 percent. Even minor changes in the strength or path of the Gulf Stream might give northern Europe a climate more like that of Siberia—an ironic consequence of polar warming.

Think About It

Find London and Stockholm on a globe. Then find cities in North America at a similar latitude. Temperatures in London and Stockholm rarely get much below freezing. How do you think their climate compares with the cities you've identified in North America? Explain the difference.

Much of humanity relies on seasonal rain

Large parts of the world, especially near the tropics, receive seasonal rains that sustain both ecosystems and human life. Seasonal rains give life, but when they fail to arrive, crop failures and famine can result. Seasonal rains can also cause disastrous flooding, as in the 2010 floods in Pakistan, which left 2 million homeless, or the 2003 floods in China, which forced 100 million people from their homes.

The most regular seasonal rains are known as **monsoons.** In India and Bangladesh, monsoon rains come when seasonal winds blow hot, humid air from the Indian Ocean (fig. 15.9). The hot land surface produces strong convection currents that lift this air, causing heavy rain across the subcontinent. When the rising air reaches the Himalayas, it rises even further, creating some of the heaviest rainfall in the world. During the five-month rainy season of 1970, a weather station in the foothills of the Himalayas recorded 25 m (82 ft) of rain!

Tropical and subtropical regions around the world have seasonal rainy and dry seasons (see the discussion of tropical biomes, chapter 5). The main reason for this variable climate is that the region of most intense solar heating and evaporation

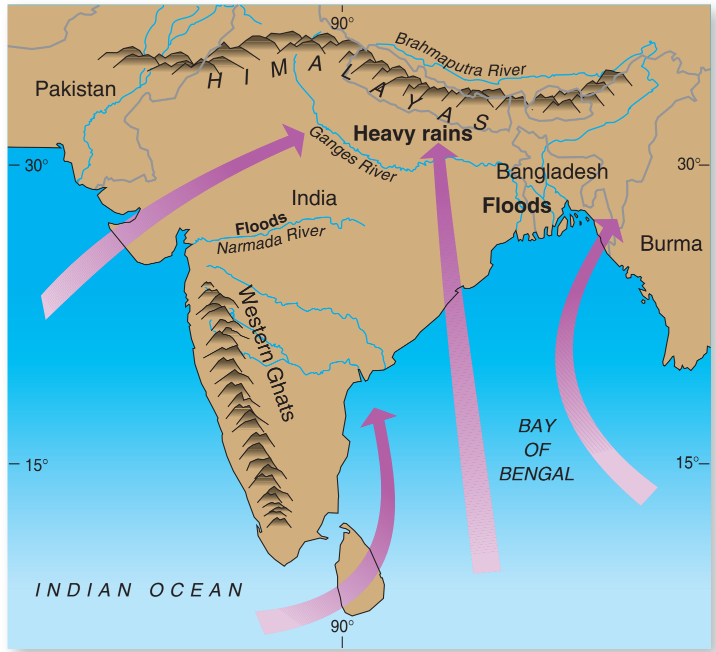


FIGURE 15.9 Summer monsoon air flows over the Indian subcontinent. Warming air rises over the plains of central India in the summer, creating a low-pressure cell that draws in warm, wet oceanic air. As this moist air rises over the Western Ghats or the Himalayas, it cools and heavy rains result. These monsoon rains flood the great rivers bringing water for agriculture, but also causing much suffering.

FIGURE 15.10 Failure of monsoon rains brings drought, starvation, and death to both livestock and people in the Sahel desert margin of Africa. Although drought is a fact of life in Africa, many governments fail to plan for it, and human suffering is much worse than it needs to be.

shifts through the year. Remember that the earth's axis of rotation is at an angle. In December and January the sun is most intense just south of the equator; in June and July the sun is most intense just north of the equator. Wherever the sun shines most directly, evaporation and convection currents—and rainfall and thunderstorms—are very strong. As the earth orbits the sun, the tilt of its axis creates seasons with varying amounts of wind, rain, and heat or cold. Seasonal rains support seasonal tropical forests, and they fill some of the world's greatest rivers, including the Ganges and the Amazon. As the year shifts from summer to winter, solar heating weakens, the rainy season ends, and little rain may fall for months.

Frontal systems create local weather

The boundary between two air masses of different temperature and density is called a front. When cooler air pushes away warmer air, we call the moving boundary a **cold front.** Cold, dense air of a cold front tends to hug the ground and push under the lighter, warmer air as it advances. As warm air is forced upward, it cools, and its cargo of water vapor condenses to water droplets or ice crystals. Air masses near the ground move slowly because of friction and turbulence near the ground surface, so upper layers of a moving air mass often move ahead of the lower layers (fig. 15.11, *below*). Notice that the region of cloud formation and precipitation is relatively narrow. Cold fronts can generate strong convective currents as they push warmer air rapidly upward. Violent winds and thunderstorms can result, with towering thunderheads. The weather after the cold front passes is usually clear, dry, and invigorating.

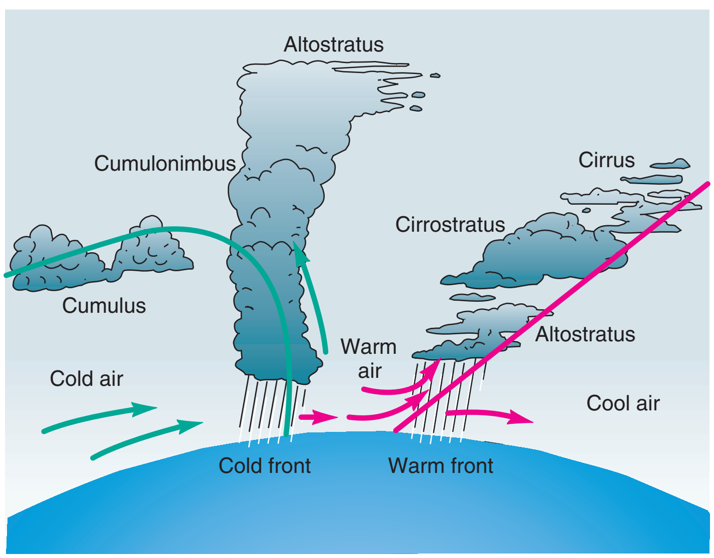


FIGURE 15.11 A cold front assumes a bulbous, "bull-nose" appearance because ground drag retards forward movement of surface air. As warm air is lifted up over the advancing cold front, it cools, producing precipitation. When warm air advances, it slides up over cooler air in front and produces a long, wedge-shaped zone of clouds and precipitation. The high cirrus clouds that mark the advancing edge of the warm air mass may be 1,000 km and 48 hours ahead of the front at ground level.

In a **warm front**, the advancing air mass is warmer than surrounding air. Because warm air is less dense than cool air, an advancing warm front will slide up over cooler air masses, creating a long, wedge-shaped profile with a broad band of clouds and precipitation (fig. 15.11, *right*). Gradual lifting and cooling in a warm front lacks the violent updrafts and strong convection currents that accompany a cold front. A warm front can have many layers of clouds at different heights. The highest layers are often wispy cirrus (mare's tail) clouds, composed mainly of ice crystals, which can extend 1,000 km (600 mi) and 2 days ahead of the front we detect at the ground level. A moist warm front can bring days of drizzle and cloudy skies.

Cyclonic storms can cause extensive damage

Severe cyclonic storms are powerful and dangerous natural forces, especially those spawned by rising, low-pressure air over warm tropical oceans. Winds swirl into this low-pressure area, turning counterclockwise in the Northern Hemisphere due to the Coriolis effect. If water vapor is abundant, as over a warm sea, the latent heat released by condensation intensifies the convection currents, which draw up more warm air and water vapor, further intensifying the wind and rain.

Called **hurricanes** in the Americas, or typhoons in the western Pacific, these storms can be hundreds of kilometers across, with winds of 320 km/hr (200 mph). Equally dangerous are the walls of water (storm surges) they push far inland (fig. 15.12*a*). In July 1931, torrential rains spawned by a typhoon caused massive flooding on China's Yangtze River that killed an estimated 3.7 million people, the largest known storm death toll in human history. A similar storm in July 1959 caused flooding of the Yellow River that killed 2 million people.

Hurricane Katrina, which devastated coastal Louisiana and the Gulf Coast in 2005, caused most of its damage with storm surges. The category 4 storm, with 232 km/hr (145 mph) winds, pushed a storm surge up to 9 m (29 ft) high onto coastal areas. Aided by shipping and oil-drilling canals, the surge destroyed large parts of New Orleans and many other cities, many of which still have not recovered (fig. 15.12*b*).

Tornadoes, swirling funnel clouds that form over land, also are considered cyclonic storms. Though never as large or powerful as hurricanes, tornadoes can be just as destructive in the limited areas where they touch down (fig. 15.12*c*). Tornadoes are generated on the American Great Plains by giant "supercell" frontal systems where strong, dry-air cold fronts from Canada collide with warm, humid air moving north from the Gulf of Mexico. Greater air temperature differences cause more powerful storms. This is why most tornadoes occur in the spring, when arctic cold fronts penetrate far south over the warming plains. As warm air rises rapidly over dense, cold air, intense vertical convection currents generate towering thunderheads with anvil-shaped leading edges and domed tops up to 20,000 m (65,000 ft) high. Water vapor cools and condenses as it rises, releasing latent heat and accelerating updrafts within the supercell. Sometimes penetrating into the stratosphere, the tops of these clouds can encounter jet streams, which help create even stronger convection currents.

(a) Hurricane Floyd, 1999 (b) Gulf Shores, Alabama, 2005 (c) A tornado touches down

FIGURE 15.12 (a) Hurricane Floyd was hundreds of kilometers wide as it approached Florida in 1999. Note the hole, or eye, in the center of the storm. (b) Destruction caused by Hurricane Katrina in 2005. More than 230,000 km^2 (90,000 mi^2) of coastal areas were devastated by this massive storm, and many cities were almost completely demolished. (c) Tornadoes are much smaller than hurricanes, but can have stronger local winds.

15.3 Natural Climate Variability

Until recently, most of us considered climate as relatively constant. Geologists and climatologists, though, have long understood that climates shift on scales of decades, centuries, and millennia. Teasing apart the simultaneous effects of multiple factors is a complex process, but expanding evidence is helping us discern the patterns. Ice cores are among our key sources of data.

Ice cores tell us about climate history

Every time it snows, small amounts of air are trapped in the snow layers. In Greenland, Antarctica, and other places where cold is persistent, yearly snows slowly accumulate over the centuries. New layers compress lower layers into ice, but still tiny air bubbles remain, even thousands of meters deep into glacial ice. Each bubble is a tiny sample of the atmosphere at the time that snow fell.

Climatologists have discovered that by drilling deep into an ice sheet, they can extract ice cores, from which they can collect airbubble samples. Samples taken every few centimeters show how the atmosphere has changed over time. Ice core records have revolutionized our understanding of climate history (see fig. 15.13). We can now see how concentrations of atmospheric CO_2 have varied. We can detect ash layers and spikes in sulfate concentrations that record volcanic eruptions. Most important, we can look at isotopes of oxygen. In cold years, water molecules with slightly lighter oxygen atoms evaporate more easily than water with slightly heavier isotopes. Consequently, by looking at the proportions of heavier and lighter oxygen atoms (isotopes), climatologists can reconstruct temperatures over time, and plot temperature changes against concentrations of CO_2 and other atmospheric gases.

The first very long record was from the Vostok ice core, which reached 3,100 m into the Antarctic ice and gives us a record of temperatures and atmospheric CO_2 over the past 420,000 years. A team of Russian scientists worked for 37 years at the Vostok site, about 1,000 km from the South Pole, to extract this ice core. A similar core has been drilled from the Greenland ice sheet.

FIGURE 15.13 Dr. Mark Twickler, of the University of New Hampshire, holds a section of the 3,000 m Greenland ice sheet core, which records 250,000 years of climate history.

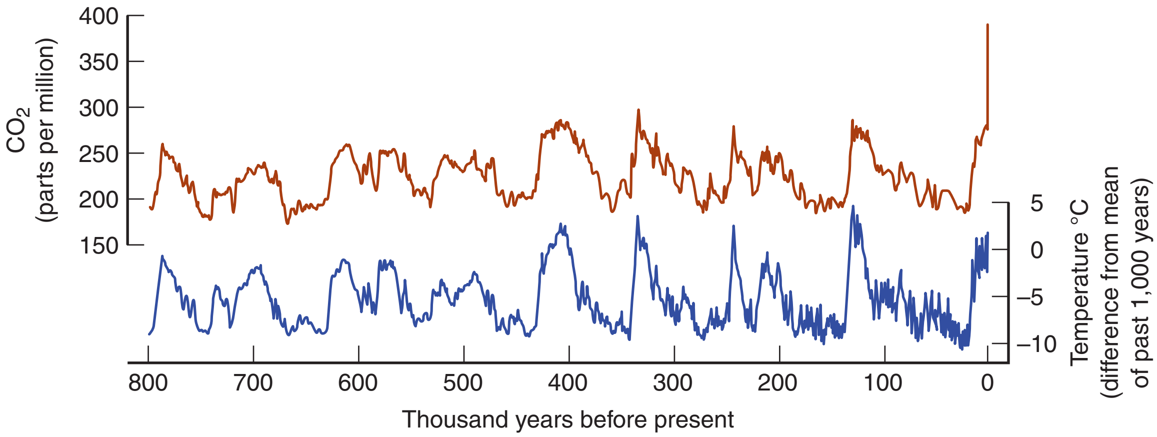


FIGURE 15.14 Atmospheric CO_2 concentrations *(red line)* map very closely to temperatures (*blue, derived from oxygen isotopes*) in air bubbles from the Antarctic Vostok ice core. Temperatures lag behind the recent jump in CO_2 possibly because the ocean has been absorbing heat. In the 800,000-year EPICA ice core there is no evidence of temperatures or CO_2 higher than that anticipated within the coming century.
Sources: UN Environment Programme; J.Bouzel et al., 2007. *EPICA Dorne C Ice Core 800KYr Deuterurm Data and Temperature Estunares.*

More recently the European Project for Ice Coring in Antarctica (EPICA) has produced a record reaching back over 800,000 years (see fig. 15.14). All these cores show that climate has varied dramatically over time but that there is a close correlation between atmospheric temperatures and CO_2 concentrations. From these ice cores, we know that CO_2 concentrations have varied between 180 to 300 ppm (parts per million) in the past 800,000 years. Therefore, we know that today's concentrations of approximately 390 ppm are about one-third higher than the earth has seen in nearly a million years. We also know that present temperatures are nearly as warm as any in the ice core record. Further warming in the coming decades is likely to exceed anything in the ice core records.

Ice core data also show that the climate is warmer now than it has been since the development of civilization, agriculture, and urbanization as we know them. We know from historical accounts that slight climate shifts can be destabilizing for human communities. During the "little ice age" that began in the 1400s, a cooling climate caused crops to fail repeatedly in agricultural regions of northern Europe. Scandinavian settlements in Greenland founded during the warmer period around A.D. 1000 lost contact with Iceland and Europe as ice blocked shipping lanes. It became too cold to grow crops, and fish that once migrated along the coast stayed farther south. The Greenland settlers died out, perhaps in battles with Inuit people who were driven south from the high Arctic by colder weather.

Evidence from ice cores drilled in the Greenland ice cap suggests that world climate can change abruptly. It appears that during the last major interglacial period, 135,000 to 115,000 years ago, temperatures flipped suddenly from warm to cold or vice versa over a period of decades rather than centuries.

Earth's movement explains some cycles

You may notice that figure 15.14 shows repeated peaks and low points. Climatologists have studied many data series like these and observed simultaneous repeating patterns of warming and cooling. The longest-period cycles are known as **Milankovitch cycles,** after Serbian scientist Milutin Milankovitch, who first described them in the 1920s. These cycles are periodic shifts in the earth's orbit and tilt (fig. 15.15). The earth's elliptical orbit stretches and shortens in a 100,000-year cycle, while the axis of rotation changes its angle of tilt in a 40,000-year cycle. Furthermore, over a 26,000-year period, the axis wobbles like an out-of-balance spinning top. These variations change the distribution and intensity of sunlight reaching the earth's surface and, consequently, global climate. Bands of sedimentary rock laid in

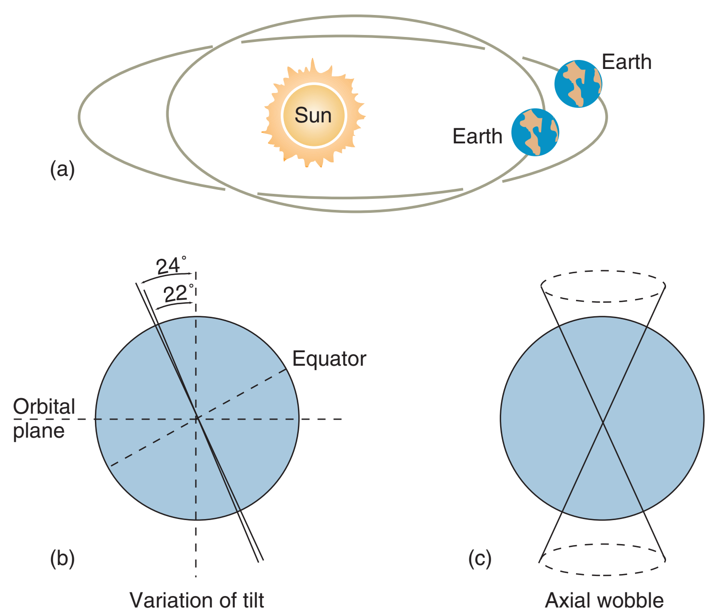


FIGURE 15.15 Milankovitch cycles, which may affect long-term climate conditions: (a) changes in the elliptical shape of the earth's orbit, (b) shifting tilt of the axis, and (c) wobble of the earth.

the oceans seem to match both these Milankovitch cycles and the periodic cold spells associated with worldwide expansion of glaciers every 100,000 years or so.

El Niño is an ocean–atmosphere cycle

On another time scale, there are decades-long oscillations in the oceans and atmosphere. Both the ocean and the atmosphere have regular patterns of flow, or currents, but these shift from time to time. As ocean currents shift, like water swirling in a bathtub, areas of warm water slosh back and forth. Sloshing in the ocean influences low-pressure areas in the atmosphere—and winds and rain change as a consequence. One important example is known as El Niño/Southern Oscillation, or ENSO.

The core of the ENSO system is a huge pool of warm surface water in the Pacific Ocean that sloshes slowly back and forth between Indonesia and South America. Most years this pool is held in the western Pacific by steady equatorial trade winds pushing ocean surface currents westward (fig. 15.16). These surface winds are strengthened by a huge low-pressure area in the warm, western Pacific. Upwelling convection currents of moist tropical air draw in winds from across the Pacific. Towering thunderheads created by rising air bring torrential summer rains to the tropical rainforests of northern Australia and Southeast Asia. Winds high in the troposphere carry a return flow back to the eastern Pacific

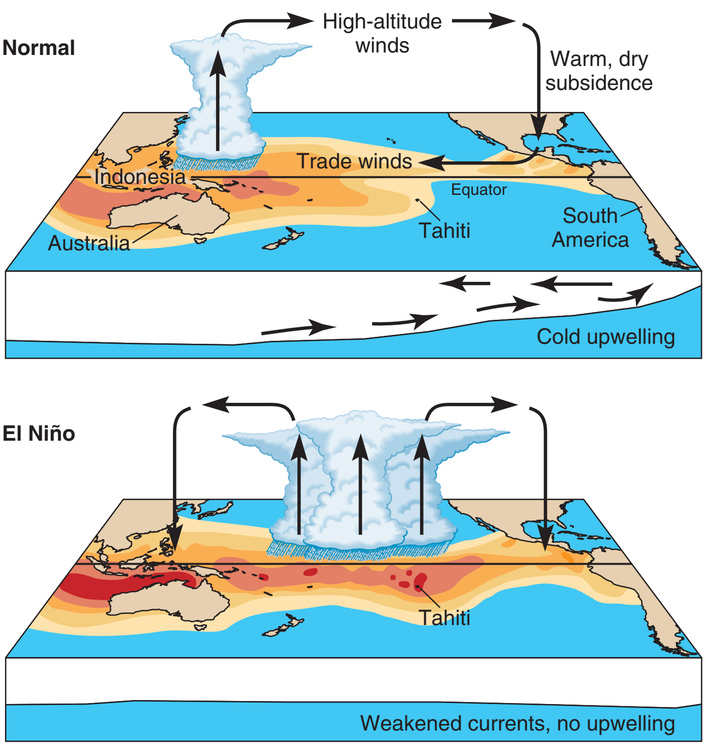


FIGURE 15.16 Normally surface trade winds drive currents from South America toward Indonesia, and cold, deep water wells up near Peru. During El Niño years, winds and currents weaken, and warm, low-pressure conditions shift eastward, bringing storms to the Americas.

where dry subsiding currents create deserts from Chile to southern California. Surface waters driven westward by the trade winds are replaced by the upwelling of cold, nutrient-rich, deep waters off the west coast of South America that support dense schools of anchovies and other fish.

Every three to five years, for reasons we don't fully understand, the Indonesian low collapses and the mass of warm surface water surges back east across the Pacific. One theory is that the high cirrus clouds reduce heating and weaken atmospheric circulation. Another theory is that eastward-flowing deep currents called baroclinic waves periodically interfere with coastal upwelling, warming the sea surface off South America and eliminating the temperature gradient across the Pacific. At any rate, the shift in position of the tropical low-pressure area has repercussions in weather systems across North and South America and perhaps around the world.

Peruvian fishermen were the first to name these irregular cycles, as weakened upwelling currents and warming water resulted in disappearance of the anchovy schools on which they depended. They named these events **El Niño** (Spanish for "the Christ child") because they were observed around Christmastime. Increased attention to these patterns has shown that sometimes, between El Niño events, coastal waters become extremely cool, and these extremes have come to be called **La Niña** (or "the little girl"). Together this cycle is called the El Niño Southern Oscillation (ENSO).

How does the ENSO cycle affect you? During an El Niño year, the northern jet stream—which normally is over Canada—splits and is drawn south over the United States. This pulls moist air inland from the Pacific and Gulf of Mexico, bringing intense storms and heavy rains from California across the Midwestern states. La Niña years bring extreme hot, dry weather to these same areas. El Niño events have brought historic floods to the Mississippi River basin, but Oregon, Washington, and British Columbia tend to be warm and dry in El Niño years. Droughts in Australia and Indonesia during El Niño episodes cause disastrous crop failures and forest fires.

ENSO-related droughts and floods are expected to intensify and become more irregular with global climate change, in part because the pool of warm water is warming and expanding. High sea surface temperatures spawn larger and more violent storms such as hurricanes. On the other hand, increased cloud cover would raise the albedo while upwelling convection currents generated by these storms could pump heat into the stratosphere. This might have an overall cooling effect, or a negative feedback in the warming climate system.

Climatologists have observed many decade-scale oscillations. The Pacific Decadal Oscillation (PDO), for example, involves a vast pool of warm water that moves back and forth across the North Pacific every 30 years or so. From about 1977 to 1997, surface water temperatures in the middle and western parts of the North Pacific Ocean were cooler than average, while waters off the western United States were warmer. During this time, salmon runs in Alaska were bountiful, while those in Washington and Oregon were greatly diminished. In 1997, however, ocean surface temperatures along the coast of western North America turned significantly cooler, perhaps marking a return to conditions that prevailed between 1947 and 1977. Under this cooler regime, Alaskan salmon runs declined while those in Washington and Oregon improved somewhat. A similar North Atlantic Oscillation (NAO), occurs between Canada and Europe.

15.4 Anthropogenic Climate Change

Many scientists regard anthropogenic (human-caused) global climate change to be the most important environmental issue of our times. The idea that humans might alter world climate is not new. In 1895 Svante Arrhenius, who subsequently received a Nobel Prize for his work in chemistry, predicted that CO_2 released by coal burning could cause global warming. At the time this idea seemed theoretical, though, and real impacts seemed unlikely.

The first data showing human impacts on atmospheric CO_2 came from an observatory on top of the Mauna Loa volcano in Hawaii. The observatory, established in 1957 as part of an International Geophysical Year, was intended to provide data on air chemistry in a remote, pristine environment. Surprisingly, measurements showed CO_2 levels increasing about 0.5 percent per year. Concentrations have risen from 315 ppm in 1958 to 392 ppm in 2011 (fig. 15.17). This graph, first produced by David Keeling at the Mauna Loa observatory, is one of the first and most important pieces of evidence that demonstrates Svante Arrhenius's prediction.

Keeling's graph has some distinctive patterns. One is the annual variation in CO_2 concentrations: every May, CO_2 levels drop slightly as plant growth on the vast northern continents capture CO_2 in photosynthesis. During the northern winter, levels rise again as respiration releases CO_2. Another pattern is that CO_2 levels are rising at an accelerating rate, currently more than 2 ppm each year. We are on track to double the preindustrial concentration of CO_2, which was 280 ppm, in about a century.

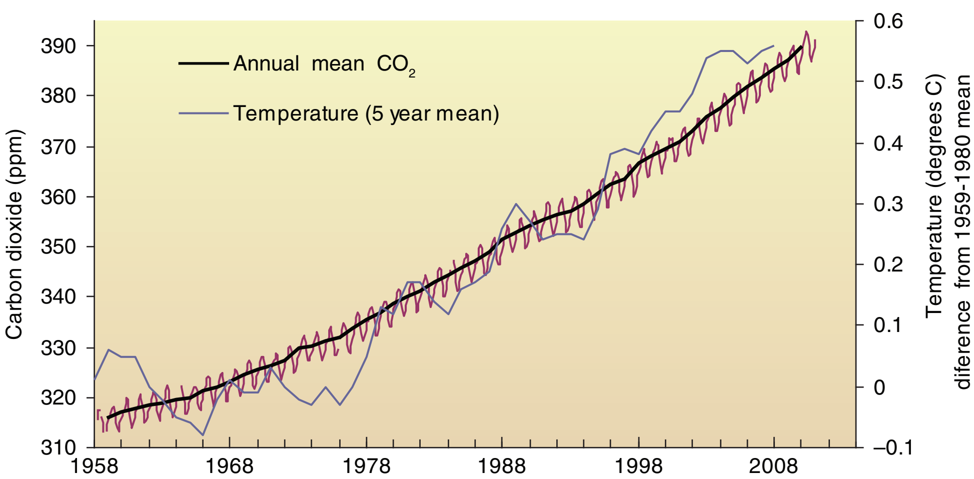


FIGURE 15.17 Measurements of atmospheric CO_2 taken at the top of Mauna Loa, Hawaii, show an increase of 1.5–2.5 percent each year in recent years. For carbon dioxide, monthly mean (red) and annual mean (black) carbon dioxide are shown. Temperature represents 5-year mean variation from the 1950–1980 mean temperature.
Source: Data from NOAA Earth System Research Laboratory, 2011.

The IPCC assesses data for policymakers

The climate system is complex, confusing, and important, so a great deal of effort has been invested in carefully and thoroughly analyzing observations like those from Mauna Loa. Since 1988 the **Intergovernmental Panel on Climate Change** (**IPCC**) has brought together scientists and government representatives from 130 countries to review scientific evidence on the causes and likely effects of human-caused climate change. The group's fourth Assessment Report (known as AR4) was published in 2007, representing six years of work by 2,500 scientists, in four volumes. This report stated that there is a 90 percent probability (it is "very likely") that recently observed climate changes result from human activities, and some changes were reported to be "virtually certain," or having a 99 percent probability of being anthropogenic (human-caused).

The wording is cautious, but it represents a remarkable unanimity for scientists, who tend to disagree and to view evidence with skepticism. Among climate scientists who consider trends in the data, there is no disagreement about whether human activities are causing current rapid climate changes. The AR4 report projected warming of about 1–6°C by 2100, depending on what policies we follow to curb climate change. The IPCC's "best estimate" for the most likely scenario was 2–4°C (3–8°F). To put that in perspective, the average global temperature change between now and the middle of the last glacial period is about 5°C. Droughts, heat stress, and increasing hurricane frequency (caused by warming oceans) could have disastrous human and economic costs. Melting ice on the Arctic Ocean, Greenland, and Antarctica was expected to contribute up to 0.6 m (about 1.5 ft) of sea-level rise.

Evidence gathered since the last IPCC report indicates that IPCC estimates were too optimistic. Increases in carbon emissions since the AR4 exceed even the worst business-as-usual model scenario published by the IPCC. Arctic ice is shrinking much more rapidly than the IPCC anticipated, and the impact on energy retention is greater than models had estimated. Revised estimates project a sea-level increase of about 1–2 m (3-6 ft) by 2100. This increase would flood populous coastal regions, including low-lying cities such as Miami, New Orleans (fig. 15.18), Boston, New York, London, and Mumbai.

FIGURE 15.18 Approximate change in land surface with the 1 m (3 ft) sea-level rise that the IPCC says is possible by the year 2100. Some analysts expect a 2 m (6 ft) rise if no action is taken.

How does climate change work?

As noted at the beginning of this chapter, the "greenhouse effect" describes the fact that gases in our atmosphere prevent long-wavelength (terrestrial) energy leaving the earth's surface from escaping to space (fig. 15.5). The energy retained in our atmosphere keeps our earth warm enough for life as we know it. Certain gases such as water (H_2O) are especially effective at blocking or absorbing this long-wavelength energy. Human activity is not drastically altering the overall concentrations of water in the atmosphere, however. Industry, forest-clearing, and agriculture have multiplied concentrations of several other greenhouse gases, however (fig. 15.18). Concentrations of these gases are low, less than 0.1 percent of the atmosphere, but multiplying even these low concentrations has considerably increased energy storage, raising both temperatures and storm activity (see section 15.1) in the atmosphere.

Carbon dioxide is the most important greenhouse gas because it is produced abundantly, it lasts decades to centuries in the atmosphere, and it is very effective at capturing long-wave energy. Emissions of CO_2 doubled in the 40 years from 1970 to 2010, from about 14 Gt/yr to more than 30 Gt/yr (fig. 15.19). Carbon dioxide contributes over three-quarters (76.6 percent) of human-caused climate impacts. Burning of fossil fuels is by far the greatest source of CO_2. Deforestation and other land-use changes are the second biggest factor. Deforestation releases carbon stored in standing trees. Organic material in the exposed soil oxidizes and decays, producing still more CO_2 and CH_4. Cement production is also an important contributor, and cement for construction has recently pushed China into the lead for global CO_2 emissions (fig. 15.20).

Methane (CH_4) from agriculture and other sources is the second most important greenhouse gas, accounting for 14 percent of our greenhouse output. Methane absorbs 23 times as much energy per gram as CO_2 does, and it is accumulating at a faster rate than CO_2. Methane is produced when plant matter decays in oxygen-free conditions, as in the bottom of a wetland. (Where oxygen is abundant, decay produces mainly CO_2). Methane is also released from natural gas wells. Rice paddies are a rich source of CH_4, as are ruminant animals, such as cattle. In a cow's stomach, which has little oxygen, digestion produces CH_4, which cows then burp into the atmosphere. A single cow can't produce much CH_4, but the global population of nearly 1 billion cattle produces enough methane to double the concentration naturally present in the atmosphere.

Nitrous oxide (N_2O), our third most important greenhouse gas, accounts for 8 percent of greenhouse gases. This gas is also released from agricultural processes, plant decay, vehicle engines, denitrification of soils, and other sources. Even though we don't produce as much N_2O as we do other greenhouse gases, this is an important gas because it is especially effective at capturing heat. Many other gases, including chlorofluorocarbons, sulfur hexafluoride, and other fluorine gases, make smaller contributions. Like N_2O and CH_4, these are emitted in relatively small amounts, but their ability to absorb specific energy wavelengths gives them a disproportionate effect.

One way to compare the importance of these various sources is to convert them all to equivalents of our most important greenhouse gas, CO_2. The units used on the *Y*-axis in fig. 15.19, gigatons of CO_2-equivalent per year (Gt CO_2 eq/yr), let us compare the effects of these sources. All four have increased, but fossil fuel burning rose the most between 1970 and 2010. This is a reason

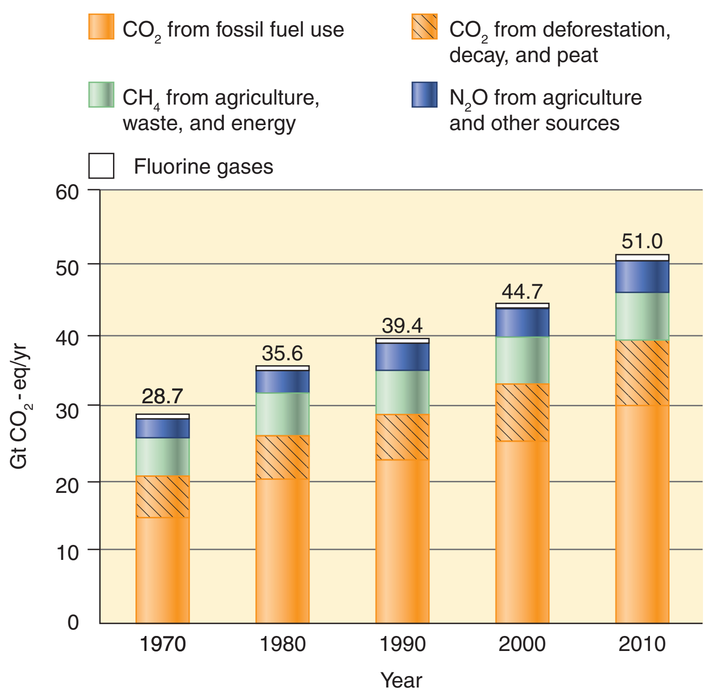


FIGURE 15.19 Contributions to climate change by different gases.
Source: IPCC, 2007.

transportation and coal-burning power plants are two of the key sectors addressed in efforts to slow climate change.

The large orange bars in fig. 15.19 show that burning fossil fuels is also our most abundant source of greenhouse gases. Electricity production, transportation, heating, and industrial activities that depend on fossil fuels together produce 50 percent of our greenhouse gases. Deforestation and agriculture account for another 30 percent. The remaining 20 percent is produced by industry.

Positive feedbacks accelerate change

As noted earlier in this chapter, the melting of polar ice is a concern because it will increase energy absorption (because water has a lower albedo than ice) and enhance warming globally. These and other feedbacks, and some tipping points at which sudden change occurs, are critical factors in climate change.

Another important feedback is the CO_2 release from warming and drying peat. Peat is soggy, semidecayed plant matter accumulated over thousands of years across the vast expanses of tundra in Canada and Siberia. As this peat thaws and dries, it oxidizes and decays, releasing more CO_2 and CH_4. A more ominous consequence of melting in the expanses of frozen arctic lands may be the release of vast stores of frozen, compressed CH_4 (methane hydrate) now locked in permafrost and ocean sediments. Release of these two carbon stores could add as much CO_2 to the atmosphere as all the fossil fuels ever burned.

Negative feedbacks are also possible: increased ocean evaporation could intensify snowfall at high latitudes, restoring some of the high-albedo snow surfaces.

How do we know recent change is human-caused?

The IPCC's third assessment report of 2001 noted that the only way to absolutely prove a human cause for climate change is to do a controlled experiment. In a controlled experiment, you keep all factors unchanging except the one you're testing, and you set aside a group of individuals—a control group—that you can later compare to the group you manipulated (see chapter 2 for more discussion of designing experiments). In the current climate manipulation experiment, however, we have only one earth to work with. So we have no controls, and we cannot keep other factors constant. What we are doing is an uncontrolled experiment—injecting carbon dioxide, methane, and other gases into the atmosphere, and observing changes that follow.

In an uncontrolled experiment, a model is usually the best way to prove cause and effect. You build a computer model, a complex set of equations, that includes variables for all the known natural fluctuations (such as the Milankovitch cycles). You also include variables for all the known human-caused inputs (CO_2, methane, aerosols, soot, and so on). Then you run the model and see if it can re-create past changes in temperatures.

If you can accurately "predict" past changes, then your model is a good description of how the system works—how the atmosphere responds to more CO_2, how oceans absorb heat, how reduced snow cover contributes feedbacks, and so on.

If you can create a model that represents the system quite well, then you can re-run the model, but this time you leave out the extra CO_2 and other factors we know that humans have contributed. If the model *without* human inputs is *inconsistent* with observed changes in temperature, and if the model *with* human inputs is *consistent* with observations, then you can be extremely confident, beyond the shadow of a reasonable doubt, that the human inputs have made the difference.

Testing detailed climate models against observed temperature trends is exactly what the IPCC and thousands of climate scientists have done in the past 20 years or so. The IPCC provided a comparison of models with and without human inputs (fig. 15.21). In all regions, the models without human inputs (blue) were significantly lower than observed climate records. Models with human-caused changes (pink) are the only way to explain recently observed increases in air temperatures, in ocean temperatures, in declining snow and ice cover, and so on. Different models in the IPCC analysis might vary in the regional severity of changes, or they might disagree on the speed of change, but the direction of change is no longer in doubt.

Scientists are generally cautious about making absolute statements. For a climate scientist, any claims of absolute proof are suspect and probably untrue. Any public statement without measures of uncertainty (how much do you really know, compared to what you don't?) is probably irresponsible. This habit of conservatism makes statements in the Fourth Assessment Report especially emphatic—for a climate scientist. When the report says that "Most of the observed increase in global average temperatures since the mid-twentieth century is *very likely* due to the observed increase in anthropogenic GHG [greenhouse gas] concentrations," it might not look like strong language to you. But this is about as vehement and unanimous a group of scientists as you're likely to find.

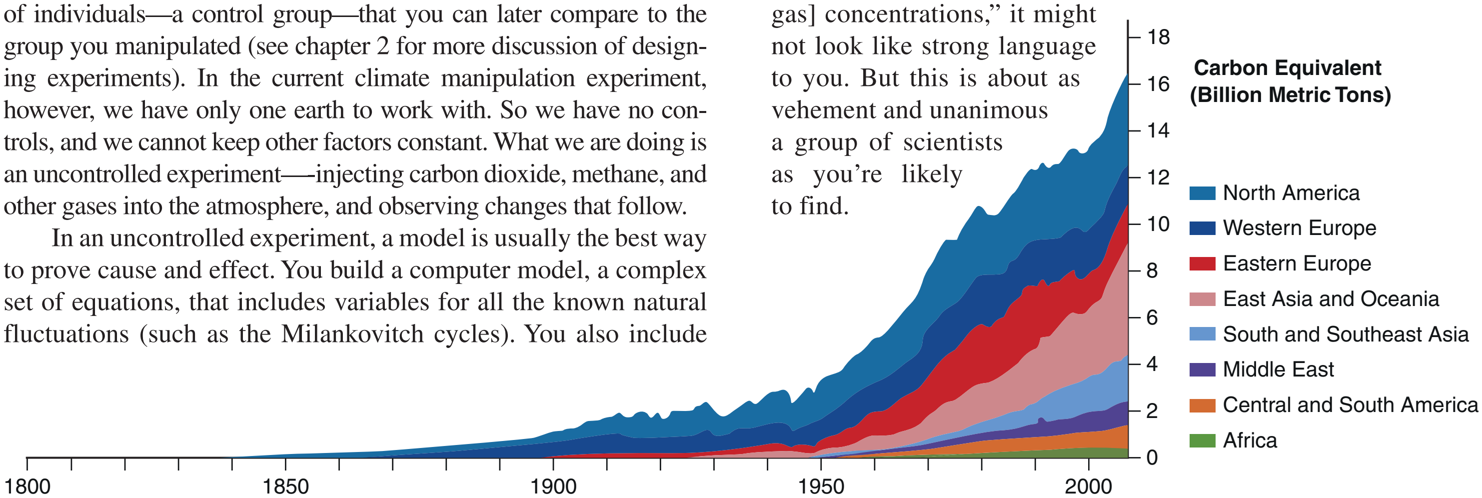


FIGURE 15.20 Carbon emissions by region since 1800. The two largest emitters, China (24%) and the United States (21%), produce nearly half of all emissions.

Data Source: Boden, T.A., G. Marland, and R.J. Andres. 2010. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

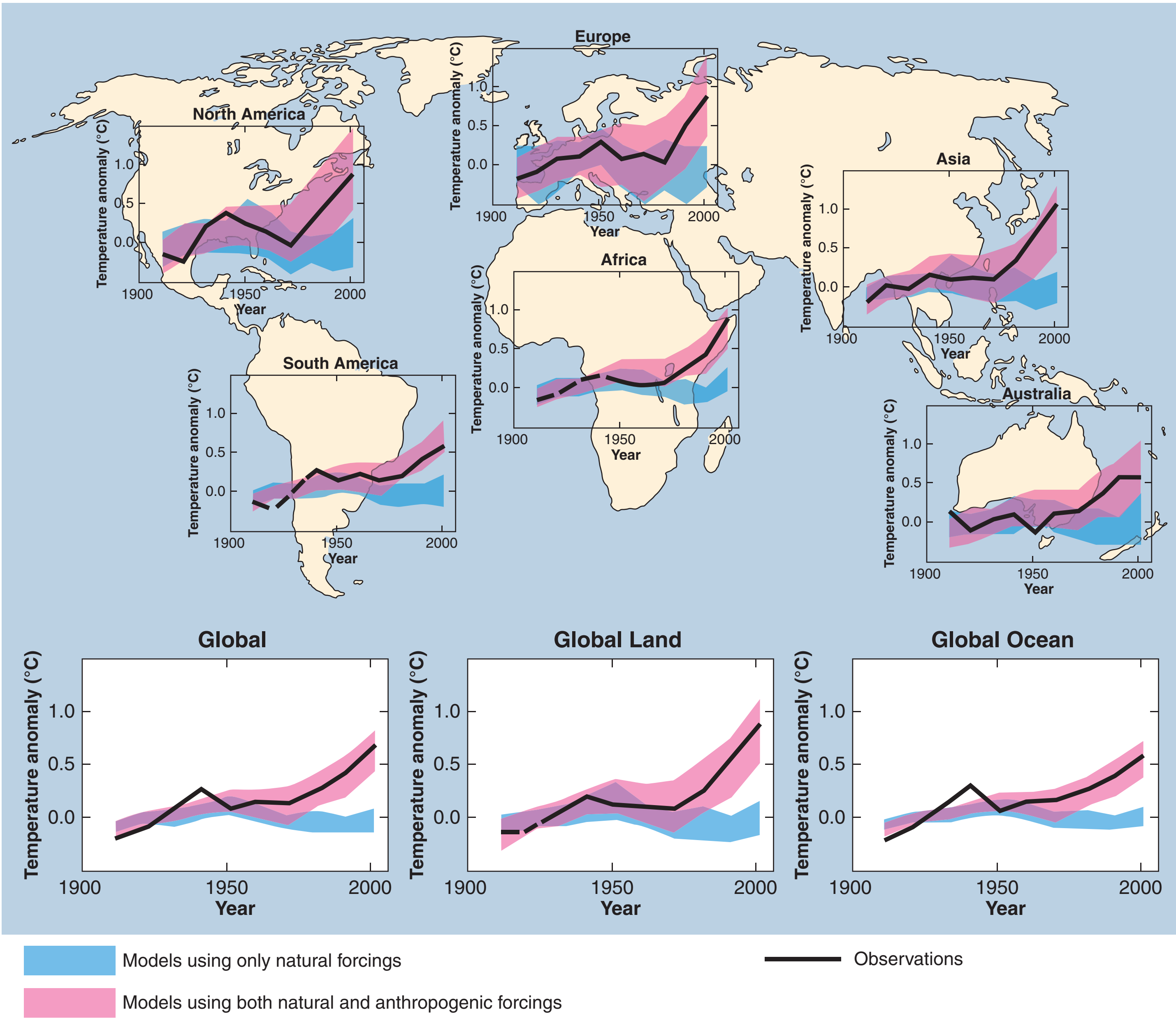


FIGURE 15.21 Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using either natural or both natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906–2005 (black line) plotted against the center of the decade and relative to the corresponding average for the period 1901–1950. Lines are dashed where spatial coverage is less than 50 percent. Blue shaded bands show the 5 to 95 percent range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Pink shaded bands show the 5 to 95 percent range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.
Source: IPCC 2007, SPM4.

15.5 What Effects are we Seeing?

The American Geophysical Union, one of the nation's largest and most respected scientific organizations, says, "As best as can be determined, the world is now warmer than it has been at any point in the last two millennia, and, if current trends continue, by the end of the century it will likely be hotter than at any point in the last two million years."

Fortunately, as shown by Socolow and Pacala (opening case study) and others, we do have options, if we chose to use them. Mitigating climate change doesn't mean reverting to the Stone Age; it mostly means investing our resources in different kinds of energy. In this section we'll examine some of the consequences of recent climate changes and some of the reasons so many scientists urge us to take action soon. Following this, we'll consider some of the many steps we can take as individuals and as a society to work for a better future.

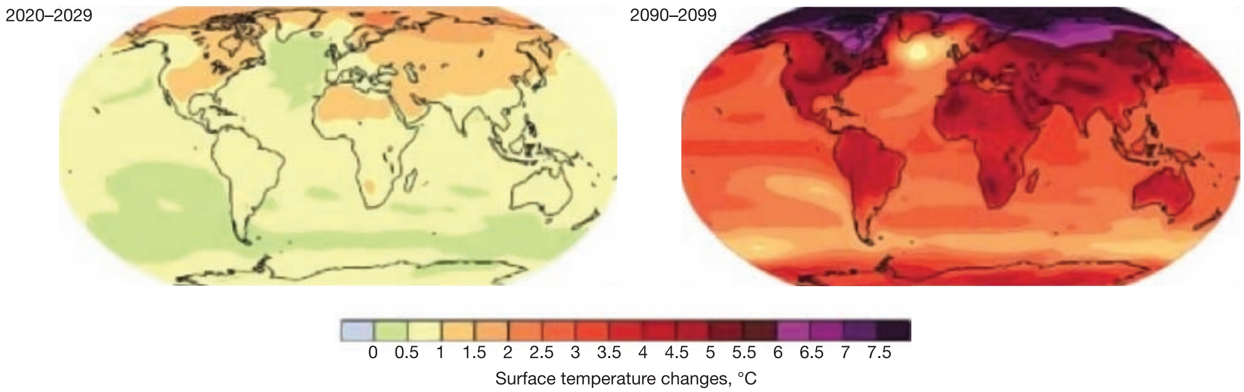


FIGURE 15.22 Surface temperature projections from IPCC scenario B1. This scenario assumes that global population peaks in midcentury and declines thereafter. It also infers rapid introduction of new, cleaner, and more-efficient technologies, but without additional climate initiatives.

Effects include warming, drying, and habitat change

Over the last century the average global temperature has climbed about 0.6°C (1°F). Nineteen of the 20 warmest years in the past 150 have occurred since 1980. New records for hot years are observed with increasing frequency. Here are some effects that have been observed:

- Polar regions have warmed much faster than the rest of the world. In Alaska, western Canada, and eastern Russia, average temperatures have increased as much as 4°C (7°F) over the past 50 years. These extremes are consistent with climate models (fig. 15.22). Permafrost is melting; houses, roads, pipelines, sewage systems, and transmission lines are being damaged as the ground sinks beneath them. Trees are tipping over, and beetle infestations (made possible by warmer winters) are killing millions of hectares of pine and spruce forest from Alaska to Colorado.
- Arctic sea ice is only half as thick now as it was 30 years ago, and the area covered by sea ice has decreased by more than 1 million km^2 (an area larger than Texas and Oklahoma combined) in just three decades. By 2040 the Arctic Ocean could be totally ice-free in the summer. This is bad news for polar bears, which depend on the ice to hunt seals. An aerial survey in 2005 found bears swimming across as much as 260 km (160 mi) of open water to reach the pack ice. When the survey was repeated after a major storm, dozens of bears were missing or spotted dead in the water. The United States has put polar bears on the endangered species list because of loss of Arctic sea ice (fig. 15.23). Loss of sea ice is also devastating for Inuit people, whose traditional lifestyle depends on ice for travel and hunting.
- Ice shelves on the Antarctic Peninsula are breaking up and disappearing rapidly, and Emperor and Adélie penguin populations have declined by half over the past 50 years as the ice shelves on which they depend for feeding and breeding disappear. Ninety percent of the glaciers on the Antarctic Peninsula are now retreating an average of 50 m per year. The Greenland ice cap also is melting twice as fast as it did a few years ago. Because ice shelves are floating, they don't affect sea level when they melt. Greenland's massive ice cap, however, holds enough water to raise sea level by about 7 m (about 23 ft) if it all melts. Melting glaciers and ice caps are contributing about 1 mm per year to sea level rise.
- Half of the world's small glaciers will disappear by 2100, according to a study of 120,000 such glaciers. Mt. Kilimanjaro has lost nearly all its famous ice cap since 1915. In 1972, Venezuela had six glaciers; now it has only two. When Montana's Glacier National Park was created in 1910, it held 150 glaciers. Now fewer than 30 remnants of glaciers remain (fig. 15.24). If current trends continue, all will have melted by 2030.

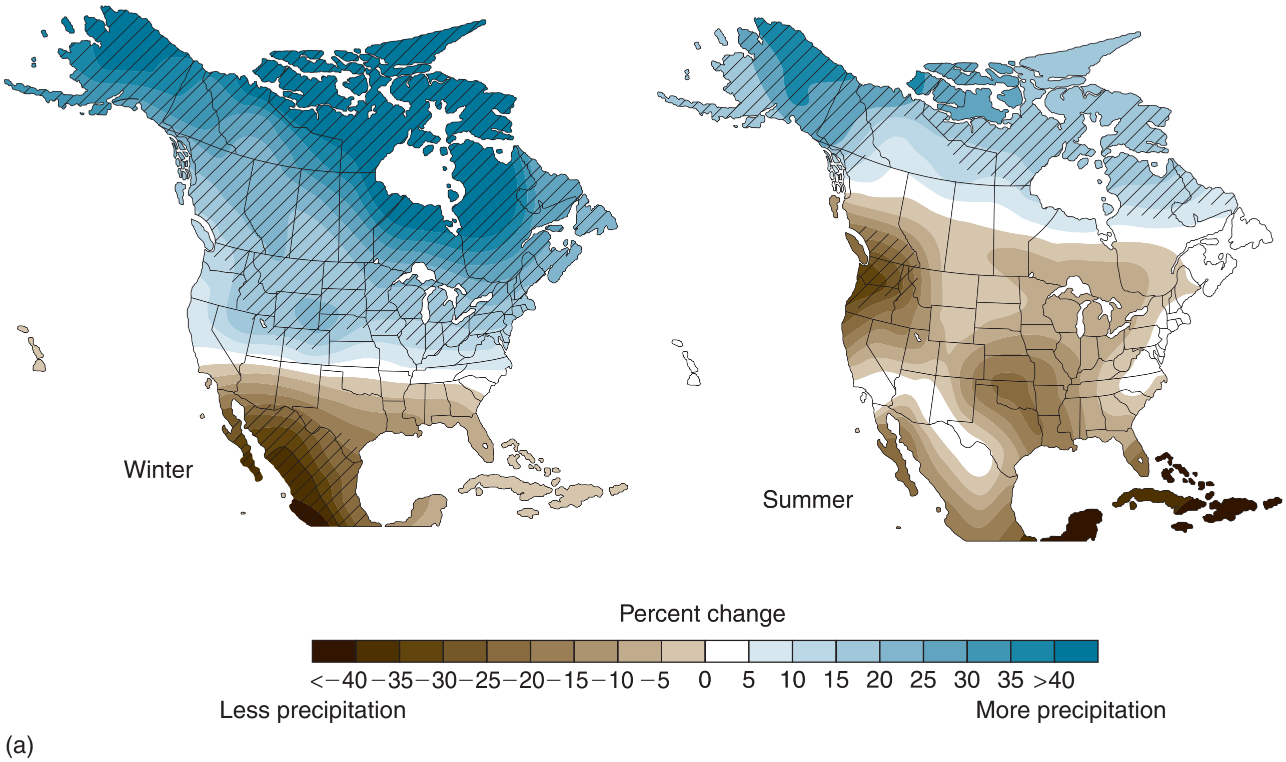
FIGURE 15.23 Diminishing Arctic sea ice prevents polar bears from hunting seals, their main food source.

FIGURE 15.24 Alpine glaciers everywhere are retreating rapidly. These images show the Grinnell Glacier in 1914 and 1998. By 2030, if present melting continues, there will be no glaciers in Glacier National Park.

- The oceans have apparently been buffering the effects of our greenhouse emissions both by absorbing CO_2 and by storing heat. Deep-diving sensors show that the oceans are absorbing 0.85 watts per m^2 more than is radiated back to space. This absorption slows current warming, but it also means that even if we reduce our greenhouse gas emissions today, it will take centuries to dissipate that stored heat. Absorbed CO_2 is also acidifying the oceans. Because shells of mollusks and corals dissolve at low pH, ocean acidity is likely to alter marine communities.
- Sea level has risen worldwide approximately 15–20 cm (6–8 in.) in the past century. About one-quarter of this increase is ascribed to melting glaciers; roughly half is due to thermal expansion of seawater. If all of Antarctica were to melt, the resulting rise in sea level could be several hundred meters.
- Droughts are becoming more frequent and widespread. In Africa, for example, droughts have increased about 30 percent since 1970. In North America, recent wet winters and hot, dry summers are consistent with climate models (fig. 15.25).
- Extreme droughts in the Amazon rainforest occurred in 2010 and 2005, the two warmest years on record thus far. These droughts, associated with high temperatures in the Atlantic, killed billions more trees than in a normal year, releasing an estimated 8 billion metric tons of CO_2 (more than China produced in 2009). A 2°C temperature rise (the best-case scenario) will destroy 20–40 percent of the Amazon forest, turning it from a carbon sink to a carbon source.
- Biologists report that many animals are breeding earlier or extending their range into new territory as the climate changes. In Europe and North America, for example, 57 butterfly species have either died out at the southern end of their range, or extended the northern limits, or both. Plants also are moving into new territories. Given enough time and a route for migration, many species may adapt to new conditions, but we now are forcing many of them to move much faster than they moved at the end of the last ice age (fig. 15.26). Insect pests and diseases have also expanded their range as hard winters have retreated northward.
- Coral reefs worldwide are "bleaching," losing their photosynthetic algae, as water temperatures rise above 30°C (85°F). With reefs nearly everywhere threatened by pollution, overfishing, and other stressors, biologists worry that rapid climate change could be the final blow for many species in these complex, biologically rich ecosystems.
- Storms are becoming stronger and more damaging. The 2005 Atlantic storm season was the most severe on record, with 26 named tropical storms, twice as many as the average over the past 30 years. This increased frequency and intensity could have other causes, but it is consistent with the expected consequences of rising sea surface temperatures.

Global warming will be costly; preventing it might not be

In 2006 Sir Nicholas Stern, former chief economist of the World Bank, issued a study on behalf of the British government on the costs of global climate change. It was one of the most strongly worded warnings to date from a government report. He said, "Scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response." Stern estimated that if we don't act soon, immediate costs of climate



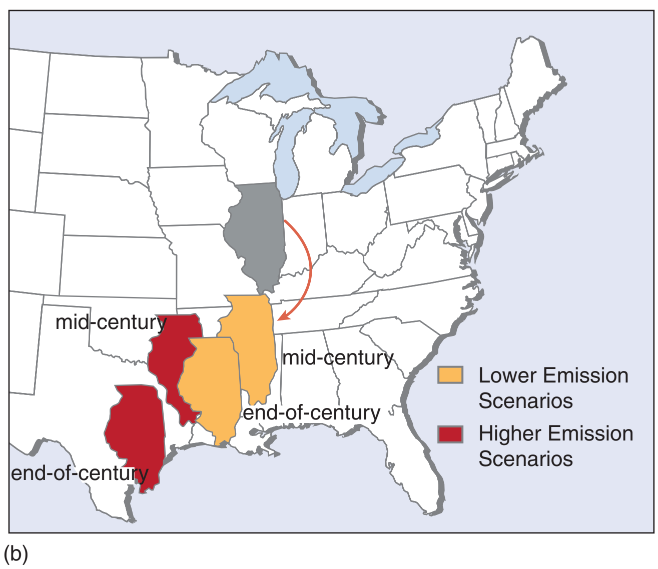


FIGURE 15.25 Models predict warmer, wetter winters and drier summers by 2100, compared to recent averages (a). Hatching marks areas with highest confidence in model projections. Midwestern farm states, the core of our food economy, will have summer climate similar to current summers in Louisiana or Texas (b).
Source: U.S. Global Change Research Program, 2009: www.globalchange.gov/usimpacts.

change will be at least 5 percent of the global GDP each year. If a wider range of risks is taken into account, the damage could equal 20 percent of the annual global economy. That would disrupt our economy and society on a scale similar to the great wars and economic depression of the first half of the twentieth century. The fourth IPCC report, meanwhile, estimated that preventing CO_2 doubling and stabilizing the world climate would cost only 0.12 percent of annual global GDP per year.

The Stern report, updated in 2009, estimates that reducing greenhouse gas emissions now to avoid the worst impacts of climate change would cost only about 1 percent of the annual global GDP. That means that $1 invested now could save us $20 later in this century. "We can't wait the five years it took to negotiate Kyoto," Sir Nicholas says. "We simply don't have time." The actions we take—or fail to take—in the next 10 to 20 years will have a profound effect on those living in the second half of this century and in the next. Energy production, Stern suggests, will have to be at least 80 percent decarbonized by 2050 to stabilize our global climate.

Those of us in the richer countries will likely have resources to blunt problems caused by climate change, but residents of poorer countries will have fewer options. The Stern report says that without action, at least 200 million people could become refugees as their homes are hit by drought or floods. Furthermore, there's a question of intergenerational equity. What kind of world are we leaving to our children and grandchildren? What price will they pay if we fail to act?

The Stern review recommends four key elements for combating climate change. They are: (1) *emissions trading* to promote cost-effective emissions reductions, (2) *technology sharing* that would double research investment in clean-energy technology and accelerate the spread of that technology to developing countries, (3) *reduction of deforestation,* which is a quick and highly

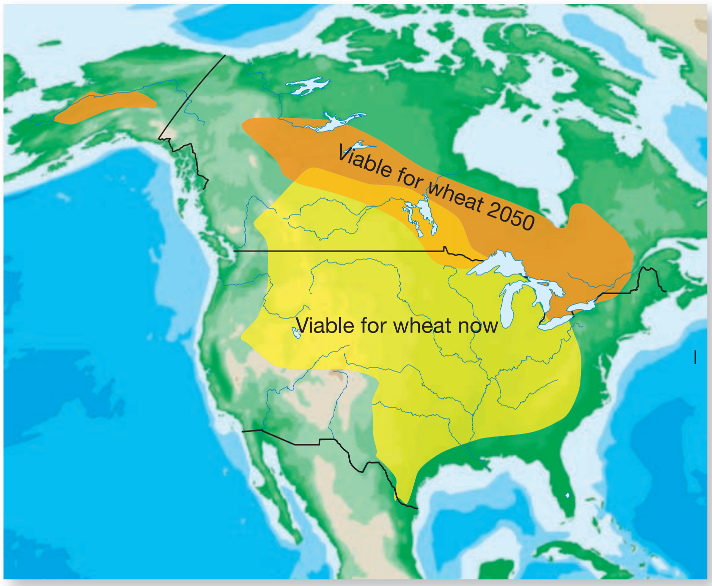


FIGURE 15.26 Most of the central United States is suitable for growing wheat now, but if current trends continue, the climatic conditions for wheat could be in central Canada in 2050.

cost-effective way to reduce emissions, and (4) *helping poorer countries* by honoring pledges for development assistance to adapt to climate change.

Sea-level change will eliminate many cities

About one-third of the world's population now live in areas that would be flooded if all of Greenland's ice were to melt. Even the 75 cm (30 in.) sea-level rise expected by 2050 will flood much of south Florida, Bangladesh, Pakistan, and many other low-lying coastal areas. Most of the world's largest urban areas are on coastlines. Wealthy cities such as New York or London can probably afford to build dikes to keep out rising seas, but poorer cities such as Jakarta, Kolkata, or Manila might simply be abandoned as residents flee to higher ground. Small island countries such as the Maldives, the Bahamas, Kiribati, and the Marshall Islands could become uninhabitable if sea levels rise a meter or more. The South Pacific nation of Tuvalu has already announced that it is abandoning its island homeland. All 11,000 residents will move to New Zealand, perhaps the first of many climate-change refugees.

Insurance companies worry that the $2 trillion in insured property along U.S. coastlines is at increased risk from a combination of high seas and catastrophic storms. At least 87,000 homes in the United States within 150 m (500 ft) of a shoreline are in danger of coastal erosion or flooding in the next 50 years. Accountants warn that loss of land and structures to flooding and coastal erosion together with damage to fishing stocks, agriculture, and water supplies could raise worldwide insurance claims from about $50 billion, which they were in the 1970s, to more than $150 billion per year in 2010. Some of this increase in insurance claims is due to the fact that more people are living in dangerous places, but extra-severe storms only exacerbate this problem.

Why are there disputes over climate evidence?

Scientific studies have long been unanimous about the direction of climate trends, but commentators on television, newspapers, and radio continue to fiercely dispute the evidence. Why is this? One reason may be that change is threatening, and many of us would rather ignore it or dispute it than acknowledge it. Another reason may be a lack of information. Another is that while scientists tend to look at trends in data, the public might be more impressed by one or two recent events, such as an especially snowy winter in their local area. And on radio and TV, colorful opinions capture more attention than data and graphs. Climate scientists offer the following responses to some of the claims in the popular media:

Reducing climate change requires abandoning our current way of life. Reducing climate change requires that we use different energy. By replacing coal-powered electricity with wind, solar, natural gas, and improved efficiency, we can drastically cut our emissions but keep our computers, TVs, cars, and other conveniences. Reducing coal dependence will also reduce financial costs of pollution damage to health and vegetation.

There is no alternative to current energy systems. As long as we invest only in fossil fuels, this will be true, but Chinese and European energy companies are creating new markets and jobs in energy and improved efficiency. Fossil fuels rely heavily on abundant public subsidies; shifting subsidies toward solar, wind, and other technologies would make these alternatives economical, and more profitable than the energy and transportation technologies of the 1940s.

A comfortable lifestyle requires high CO_2 output. Most northern Europeans produce half the CO_2 of North Americans, per capita. Yet they have higher standards of living (in terms of education, health care, life span, vacation time, financial security) than North Americans. Residents of San Francisco consume about one-sixth as much energy as residents of Kansas City, yet quality of life is not necessarily six times greater in Kansas City than in San Francisco.

Natural changes such as solar variation can explain observed warming. Solar input fluctuates, but the changes are slight and do not coincide with the direction of changes in temperatures. Milankovitch cycles also cannot explain the rapid changes in the past few decades. Increased observed temperature and sea-level changes, however, do correspond closely with GHG emissions (fig. 15.19).

The climate has changed before, so this is nothing new. Today's CO_2 level of roughly 392 ppm exceeds by at least 30 percent anything the earth has seen for nearly a million years, and perhaps as long as 15 million years. Antarctic ice cores indicate that CO_2 concentrations for the past 800,000 years have varied from 180 to 300 ppm (see fig. 15.14). This natural variation in CO_2 appears to be a feedback in glacial cycles, resulting from changes in biotic activity in warm periods. Because temperature closely tracks CO_2, temperatures by 2100 are likely to exceed anything in the past million years. The rate of change is probably also unprecedented. Changes that took 1,000 to 5,000 years at the end of ice ages are now occurring on the scale of a human lifetime.

Temperature changes are leveling off. Over short time frames, temperature trends vary (fig. 15.1), but over decades the trends in surface air temperatures and in sea level continue to rise.

We had cool temperatures and snowstorms last year, not heat and drought. Regional differences in temperature and precipitation trends are predicted by climate models. Most of the United States is expected to see wetter, warmer winters and drier, hotter summer (fig. 15.25).

Climate scientists don't know everything, and they have made errors in the past. The gaps and uncertainties in climate data are minute compared to the evident trends. There are many unknowns—details of precipitation change or interaction of long-term cycles such as El Niño—but the trends are unequivocal. Climatologist James Hansen has noted that while most people make occasional honest mistakes, fraud in data collection is almost unheard of. This is because transparency in the scientific process ensures public visibility of errors. There is much less public accountability in popular media, however, where climate scientists are regularly subjected to personal attacks from climate-change deniers.

15.6 Envisioning Solutions

Dire warnings of climate change are intimidating, but in response, individuals and communities around have been working on countless promising and exciting strategies to mitigate these changes. All of these efforts, at all scales, are valuable. In this section we'll look at some of these strategies. Curbing climate change is a daunting task, but it is also full of opportunity.

We can establish new rules and standards

In 1997 a meeting in Kyoto, Japan, called together climate scientists and government representatives from around the globe. This meeting was a follow-up to the 1992 Earth Summit in Rio de Janeiro, Brazil, at which most nations had agreed in principle that sustainable development—equitable growth that doesn't destroy opportunities for future generations—was a good idea. The **Kyoto Protocol** (agreement) followed this general principle and called on nations to roll back emissions of CO_2, CH_4, and N_2O. The goal was to reach 5 percent below 1990 levels by 2012. Poorer nations, such as India and China, were exempt, allowing them to expand their economies and improve standards of living.

The Kyoto protocol went into effect in 2005. Each country signing the agreement is now responsible for following through and reducing emissions. Considerable progress has occurred, especially in western Europe, but most countries are behind their Kyoto targets. Among developed nations, only the United States and Australia still declined to sign the protocol. The United States has persistently claimed that reducing carbon emissions would be too costly and that we must "put the interests of our own country first and foremost."

Many other smaller agreements have followed Kyoto. New policy strategies have also been implemented, including carbon-trading markets in Europe, Asia, and North America. In carbon trading, or cap-and-trade systems, legal limits are set on emissions, and countries with lower emissions can sell their emissions credits, or their "right to pollute," to someone else. The Kyoto Protocol promoted this approach.

The global market for trading carbon emission credits has grown rapidly. In 2006 about 700 million tons of carbon equivalent credits were exchanged, with a value of some $3.5 billion. By 2010, trade had grown to 7 billion tons, despite economic slowdowns that reduced carbon emissions, and thus prices for carbon credits, in 2009.

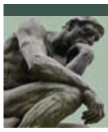
Business groups are understandably wary of changing rules, but increasingly they are saying that they can accept new standards if they are clear and fairly applied. In 2007 the heads of ten of the largest business conglomerates in America joined four environmental groups to call for strong national legislation to achieve significant reductions in greenhouse gases. The corporations included Alcoa, BP America, Caterpillar, DuPont, General Electric, and others. The nongovernmental organizations were Environmental Defense, the Pew Center, Natural Resources Defense Council, and World Resources Institute. That initiative was expanded in 2009 by the group Business for Innovative Climate & Energy Policy (BICEP), which has asked the Obama administration to reduce greenhouse gases by 80 percent below 1990 levels by 2050. Members of this group, including Gap, Inc., eBay, and others have received support from EPA administrator Lisa Jackson.

These companies want the U.S. economy to remain competitive as international policies about greenhouse gases change. They also prefer a single national standard rather than a jumble of conflicting local and state rules. This complex landscape of differing rules is a very real possibility, as many states and cities are beginning to lead the way in curbing their own emissions (What Do You Think? p. 339). Knowing that climate controls are inevitable, businesses want to know now how they'll have to adapt, rather than wait until a crisis causes us to demand sudden, radical changes.

Stabilization wedges could work now

As discussed in the opening case study, the idea of stabilization wedges is that they can work just by expanding currently available technologies. To stabilize carbon emissions, we would need to cut about 7 GT in 50 years; to reduce CO_2, as called for in the Kyoto Protocol, we could add another seven wedges (fig. 15.2).

Because most of our CO_2 emissions come from fossil fuel combustion, energy conservation and a switch to renewable fuels are important. Doubling vehicle efficiency and halving the miles we drive would add up to 1.5 of the 1-GT wedges. Installing efficient lighting and appliances, and insulating buildings, could add up to another 2 GT. Capturing and storing carbon released by power plants, gas wells, and other sources could save another gigaton.



What Do You Think?

States Take the Lead on Climate Change

In 2006, California passed a groundbreaking law that places a cap on emissions of carbon dioxide and other global warming gases from utilities, refineries, and manufacturing plants. The law aims to roll back the state's greenhouse gas releases to 1990 levels (a reduction of 15 percent) by 2020, and to 80 percent below 1990 levels by 2050. Reductions involve enforceable caps on emissions, monitored through regular industry emissions reports. Companies that cut emissions below their maximum allowance can profit by selling credits to other companies that have not met their caps. Putting a price on carbon emissions is creating incentives for innovation, which can now be cheaper than polluting. At the same time the cost of implementing the plan is low, and industries can meet standards in any way they choose. The legislation addresses a wide range of carbon sources, including agriculture, cement production, electricity generation, and suburban sprawl. Utilities and corporations are also prohibited from buying power from out-of-state suppliers whose sources don't meet California's emission standards. All these can be seen online at the "California Climate Change Portal."

This rule is the most aggressive climate-change effort of any state, but California voters strongly support it. When the energy industry challenged it in a ballot initiative in 2010, claiming it would cost the state jobs, 62 percent of voters still voted to keep the law. California has often led the way in improving air quality. In 2004 the state passed revolutionary legislation that required automakers to cut tailpipe emissions of carbon dioxide from cars and trucks, which has since been picked up by New York and other states. When car manufacturers failed to comply, California sued the six largest automakers in 2006, charging that they were costing the state billions of dollars in health and environmental damages.

What inspires such revolutionary steps? One factor is that California's economy relies almost entirely on declining winter snowpack for both urban water use and farm irrigation. Recent years of severe droughts have affected much of the state and worried cities and counties. Californians also have gotten tired of waiting for action in Washington, where the dominant view has been that climate controls will cost jobs. Contrary to this argument, California has seen rapid job growth in clean energy. Between 1995 and 2008, clean-energy businesses grew by 45 percent, 10 times the state's average growth rate. Clean energy employs over 500,000 people and has brought in over $9 billion in venture capital, or 60 percent of all clean-energy investments nationwide.

Following this lead, most U.S. states and more than 500 cities have taken steps to promote renewable energy and reduce greenhouse gas emissions. Massachusetts announced in 2010 that, like California, it will cut greenhouse gases by 25 percent by 2020. Strategies the states are taking include efficient building standards, support for alternative energy, more-efficient distribution grids, land-use planning standards, support for retrofitting old houses, and auto insurance incentives for efficient vehicles.

Carbon trading has also caught on, with 27 states and four Canadian provinces participating in three regional carbon-trading compacts—the Midwestern Greenhouse Gas Reduction Accord, the Western Climate Initiative, and the northeastern Regional Greenhouse Gas Initiative. The northeastern compact (RGGI) began trading carbon credits for 233 plants in 2008. By 2010, carbon credit auctions produced more than $700 million in revenue to support conservation and alternative energy initiatives in participating states.

Carbon trading is not perfect: carbon prices are often too low to provide real incentives for some industries; many question whether a "right to pollute" is the best strategy; and carbon revenues risk being diverted to states' general funds, as happened in New York in 2010. However, these compacts are widely considered successful—and palatable—approaches to reducing emissions.

New rules are a challenge to industry, but they can also lead to greater efficiency in operations, and changes are generally manageable if they are predictable and evenly applied. Still, these rules have been difficult to establish in Washington. If you were in Congress, what evidence would you want to see in order to buy into some of these state-led innovations?

Pacala and Socolow's original 14 wedges are paraphrased in table 15.3. As the authors note, nobody will agree that all the wedges are a good idea, and all have some technological limitations, but none are as far off as revolutionary technologies such as nuclear fusion. Some analysts have subsequently proposed still additional wedges, and technologies that make these wedges possible, or that point to new ones, are changing rapidly.

Alternative practices can be important

Carbon capture and storage, one of the important stabilization wedges, is beginning to be widely practiced. Norway's state oil company, Statoil, which extracts oil and gas from beneath the North Sea, has been pumping more than 1 million metric tons of CO_2 per year into an aquifer 1,000 m below the seafloor at one of its North Sea gas wells. Injecting CO_2 increases pressure on oil reservoirs and enhances oil recovery. It also saves money because the company would have to pay a $50 per ton carbon tax on its emissions. Around the world, deep saltwater aquifers could store a century's worth of CO_2 at current fossil fuel consumption rates.

Carbon capture and injection is widely practiced for improving oil and gas recovery, so the technology is available (fig. 15.27). There are concerns about leaking from deep storage, but the main concern is that there have been few compelling economic arguments. Carbon taxes, or carbon trading, could be strategies to justify carbon capture.

Most attention is focused on CO_2 because it is our most abundant greenhouse gas, but methane is also important because, although we produce less of it, methane is a much more powerful absorber of infrared energy. Some atmospheric scientists think the best short-term strategy might be to focus on methane.

Methane from landfills, oil wells, and coal mines is now being collected in some places for fuel. Rice paddies are another major methane source. Changing flooding schedules and fertilization techniques can reduce some of these emissions. Reducing gas pipeline leaks would conserve this resource as well as reduce warming. Finally, ruminant animals (such as cows, camels, sheep)

Table 15.3 Actions to Reduce Global CO_2 Emissions by 1 Billion Tons over 50 Years
1. Double the fuel economy for 2 billion cars from 30 to 60 mpg.
2. Cut average annual travel per car from 10,000 to 5,000 miles.
3. Improve efficiency in heating, cooling, lighting, and appliances by 25 percent.
4. Update all building insulation, windows, and weather stripping to modern standards.
5. Boost efficiency of all coal-fired power plants from 32 percent today to 60 percent (through co-generation of steam and electricity).
6. Replace 800 large coal-fired power plants with an equal amount of gas-fired power (four times current capacity).
7. Capture CO_2 from 800 large coal-fired or 1,600 gas-fired, power plants and store it securely.
8. Replace 800 large coal-fired power plants with an equal amount of nuclear power (twice the current level).
9. Add 2 million 1 MW windmills (50 times current capacity).
10. Generate enough hydrogen from wind to fuel a billion cars (4 million 1 MW windmills).
11. Install 2,000 GW of photovoltaic energy (700 times current capacity).
12. Expand ethanol production to 2 trillion liters per year (50 times current levels).
13. Stop all tropical deforestation and replant 300 million ha of forest.
14. Apply conservation tillage to all cropland (10 times current levels).

Source: Data from Pacala and Socolow, 2004.

are a major source of methane. Modifying human diets, including less beef consumption, could reduce methane significantly.

There are many regional initiatives

Many countries are working to reduce greenhouse emissions. The United Kingdom, for example, had already rolled CO_2 emissions back to 1990 levels by 2000 and vowed to reduce them 60 percent by 2050. Britain already has started to substitute natural gas for coal, promote energy efficiency in homes and industry, and raise its already high gasoline tax. Plans are to "decarbonize" British society and to decouple GNP growth from CO_2 emissions. A revenue-neutral carbon levy is expected to lower CO_2 releases and trigger a transition to renewable energy over the next five decades. In 2007, New Zealand's prime minister, Helen Clark, pledged that her country would be **carbon neutral** by 2025, through a combination of wind and geothermal energy, carbon capture on farms, and other strategies.

Germany also has reduced its CO_2 emissions at least 10 percent by switching from coal to gas and by encouraging energy efficiency throughout society. Atmospheric scientist Steve Schneider calls this a "no regrets" policy—even if we don't need to stabilize our climate, many of these steps save money, conserve resources, and have other environmental benefits. Nuclear power also is being promoted as an energy alternative that produces no greenhouse gases directly and that provides high-volume, centralized power production. It remains an imperfect option because greenhouse gases and other pollutants are produced in mining, processing, and transporting nuclear fuel. There are also security worries and unresolved problems of how to store wastes safely. Still this is an option favored by many states and utility companies.

Many people believe renewable energy sources offer the best solution to climate problems. Chapter 20 discusses options for conserving energy and switching to renewable sources, such

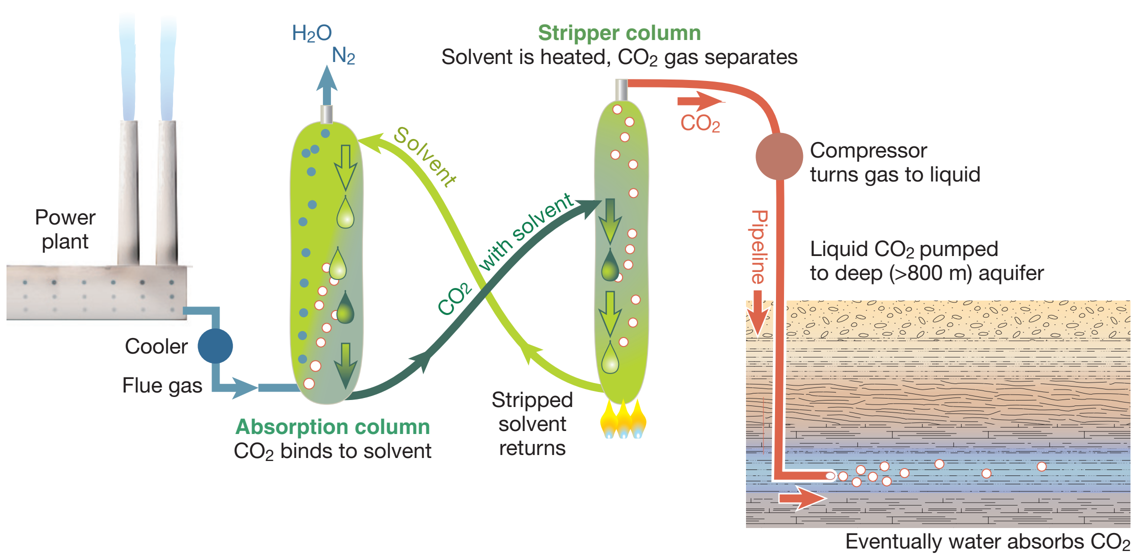


FIGURE 15.27 One method of carbon capture and storage uses a liquid solvent, such as ammonia, to capture CO_2. Steam and nitrogen are released, and the CO_2 is compressed and pumped to deep aquifers for permanent storage.

What Can You Do?

Reducing Carbon Dioxide Emissions

Individual actions can have tremendous impacts on climate change, because our actions are multiplied by the millions of others who make similar decisions. Many of existing options save money in the long run and have other benefits such as reducing pollution and resource consumption.

The most obvious strategies involve domestic transportation, heating, and lighting, which together make up roughly 40 percent of our national production of CO_2. You can drive less, walk, bike, take public transportation, carpool, or buy a vehicle that gets at least 30 mpg (12.6 km/l). Average annual CO_2 reductions are about 20 lbs (9 kg) for each gallon of gasoline saved. Replacing standard incandescent light bulbs with compact fluorescents or other efficient bulbs is another easy and money-saving fix. Average annual CO_2 reductions are about 500 lbs (0.23 metric tons) per bulb, or 10,000 lbs (4.6 metric tons) for every 20 bulbs in your household.

A recent study of behavior and household options found that we could reduce U.S. emissions by 233 metric tons of carbon with these simple changes. These strategies—another example of wedge analysis at the household level—could reduce total emissions by 7.4 percent in 10 years without any new regulations, technology, or reductions in well-being. Transportation efficiency would make the most rapid difference (fig. 1).

To read more, see T. Dietz et al., 2009. Household actions can provide a behavioral wedge to rapidly reduce U.S. carbon emissions. *Proceedings of the National Academy of Sciences* 106(44): 18452–56

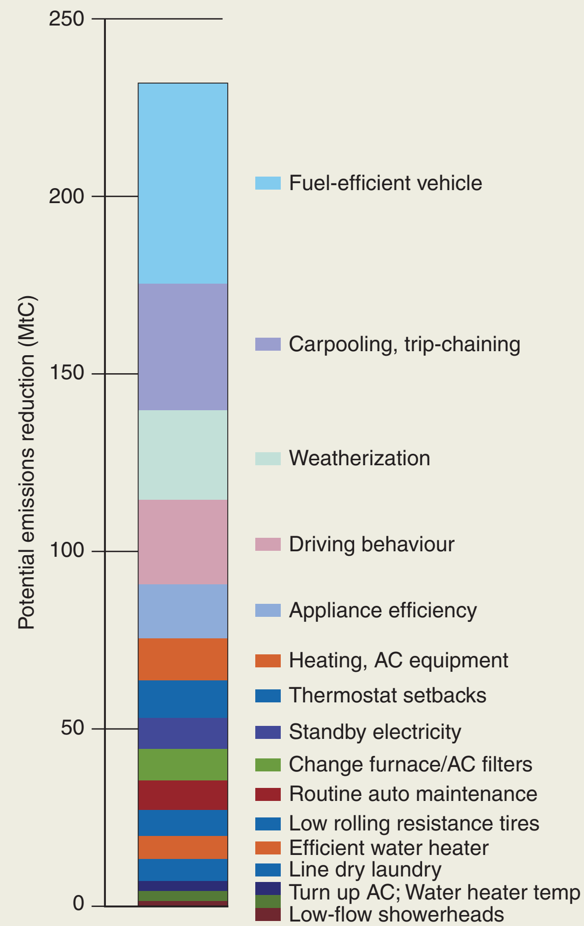


FIGURE 1 Potential impact on emissions in 10 years if available strategies were widely adopted.

Adapted from Dietz at., 2009.

as solar, wind, geothermal, biomass, and fuel cells. Denmark, the world's leader in wind power, now gets 20 percent of its electricity from windmills. Plans are to generate half of the nation's electricity from offshore wind farms by 2030.

Countless individual cities and states have announced their own plans to combat global warming. Among the first of these were Toronto, Copenhagen, and Helsinki, which pledged to reduce CO_2 emissions 20 percent from 1990 levels by 2010. Some corporations are following suit. British Petroleum set a goal of cutting CO_2 releases from all its facilities by 10 percent before 2010. Each of us can make a contribution in this effort. As Professor Socolow and his colleagues point out, simply driving less and buying high-mpg vehicles could save about 1.5 billion tons of carbon emissions by 2054 (fig. 15.28; What Can You Do? see above).

FIGURE 15.28 Burning fossil fuels produces about half our greenhouse gas emission, and transportation accounts for about half of our fossil fuel consumption. Driving less, choosing efficient vehicles, carpooling, and other conservation measures are among our most important personal choices in the effort to control global warming.

In the midst of all the debate about how serious the consequences of global climate change may or may not be, we need to remember that many of the proposed solutions are advantageous in their own right. Even if climate change turns out not to be as much of a threat as we think now, they have other positive benefits. Moving from fossil fuels to renewable energy sources such as solar or wind power, for example, would free us from dependence on foreign oil and improve air quality. Planting trees makes cities pleasant places to live and provides habitat for wildlife. Making buildings more energy efficient and buying efficient vehicles saves money now and in the long run. Walking, biking, and climbing stairs are good for your health, and they help reduce traffic congestion and energy consumption. Reducing waste, recycling, and other forms of sustainable living improve our environment in many ways in addition to helping fight climate change. It's important to focus on these positive effects rather than to look only at the gloom-and-doom scenarios for global climate catastrophes. As the Irish statesman and philosopher Edmund Burke said, "Nobody made a greater mistake than he who did nothing because he could do only a little."

CONCLUSION

Climate change may be the most far-reaching issue in environmental science today. Although the challenge is almost inconceivably large, solutions are possible if we choose to act, as individuals and as a society. Temperatures are now higher than they have been in thousands of years, and climate scientists say that if we don't reduce greenhouse gas emissions soon, drought, flooding of cities, and conflict may be inevitable. The "stabilization wedge" proposal is a list of immediate and relatively modest steps that could be taken to accomplish needed reductions in greenhouse gases.

Understanding the climate system is essential to understanding the ways in which changing composition of the atmosphere (more carbon dioxide, methane, and nitrous oxide, in particular) matters to us. Basic concepts to remember about the climate system include how the earth's surfaces absorb solar heat, how atmospheric convection transfers heat, and that different gases in the atmosphere absorb and store heat that is reemitted from the earth. Increasing heat storage in the lower atmosphere can cause increasingly vigorous convection, more extreme storms and droughts, melting ice caps, and rising sea levels. Changing patterns of monsoons, cyclonic storms, frontal weather, and other precipitation patterns could have extreme consequences for humans and ecosystems.

Despite the importance of natural climate variation, observed trends in temperature and sea level are more rapid and extreme than other changes in the climate record. Exhaustive modeling and data analysis by climate scientists show that these changes can be explained only by human activity. Increasing use of fossil fuels is our most important effect, but forest clearing, decomposition of agricultural soils, and increased methane production are also extremely important.

International organizations, national governments, and local communities have all begun trying to reverse these changes. Individual actions and commitment are also essential if we are to avoid dramatic and costly changes in our own lifetimes.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

15.1 Describe the general composition and structure of the atmosphere.

- Absorbed solar energy warms our world.
- The greenhouse effect is energy captured by gases in the atmosphere.
- Evaporated water stores energy, and winds redistribute it.

15.2 Explain why weather events follow general patterns.

- Why does it rain?
- The Coriolis effect explains why winds seem to curve.
- Ocean currents modify our weather.
- Much of humanity relies on seasonal rain.
- Frontal systems create local weather.
- Cyclonic storms cause extensive damage.

15.3 Outline some factors in natural climate variability.

- Ice cores tell us about climate history.
- The earth's movement explains some cycles.
- El Niño is an ocean–atmosphere cycle.

15.4 Explain the nature of anthropogenic climate change.

- The IPCC assesses data for policymakers.
- How does climate change work?
- Positive feedbacks accelerate change.
- How do we know recent change is human-caused?

15.5 What effects are we seeing?

- Effects include warming, drying, and habitat change.
- Global warming will be costly; preventing it might not be.
- Sea-level change will eliminate many cities.
- Why are there disputes over climate evidence?

15.6 Identify some solutions to slow climate change.

- We can establish new rules and standards
- Stabilization wedges could work now.
- Alternative practices can be important.
- There are many regional initiatives.

PRACTICE QUIZ

1. What are the dominant gases that make up clean, dry air?
2. Name and describe four layers of the atmosphere.
3. What is the greenhouse effect? What is a greenhouse gas?
4. What are some factors that influence natural climate variation?
5. Explain the following: Hadley cells, jet streams, Coriolis effect.
6. What is a monsoon, and why is it seasonal?
7. What is a cyclonic storm?
8. Identify 5 to 10 actions we take to increase greenhouse gases in the atmosphere.
9. What is the IPCC, and what is its function?
10. What method has the IPCC used to demonstrate a human cause for recent climate changes? Why can't we do a proper manipulative study to prove a human cause?
11. List 5 to 10 effects of changing climate.
12. What is a climate stabilization wedge? Why is it an important concept?
13. What is the Kyoto Protocol?
14. List several actions cities, states, or countries have taken to unilaterally reduce greenhouse gas emissions.

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. Weather patterns change constantly over time. From your own memory, what weather events can you recall? Can you find evidence in your own experience of climate change? What does your ability to recall climate changes tell you about the importance of data collection?
2. Many people don't believe that climate change is going on, even though climate scientists have amassed a great deal of data to demonstrate it. What factors do you think influence the degree to which a person believes or doesn't believe climatologists' reports?
3. How does the decades-long, global-scale nature of climate change make it hard for new policies to be enacted? What factors might be influential in people's perception of the severity of the problem?
4. What forces influence climate most in your region? in neighboring regions? Why?
5. Of the climate wedges shown in table 15.3, which would you find most palatable? least tolerable? Why? Can you think of any additional wedges that should be included?
6. Would you favor building more nuclear power plants to reduce CO_2 emissions? Why or why not?

Data Analysis: Examining the IPCC Fourth Assessment Report (AR4)

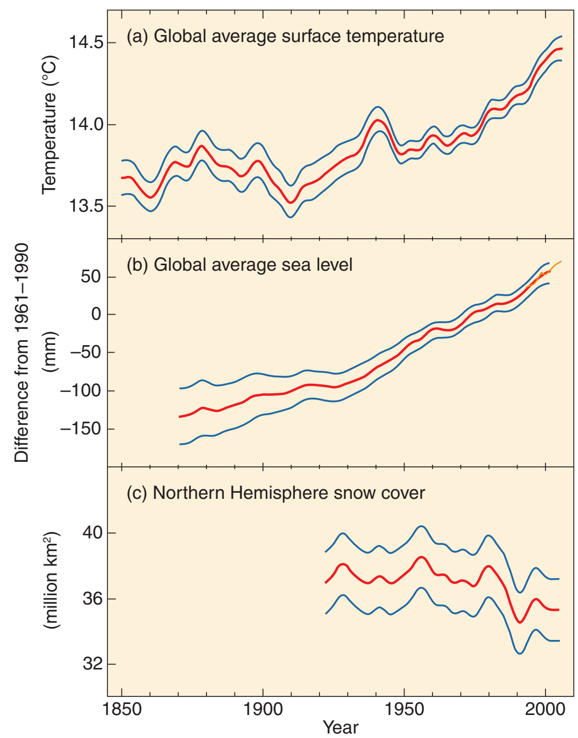
The Intergovernmental Panel on Climate Change (IPCC) has a rich repository of figures and data, and because these data are likely to influence some policy actions in your future, it's worthwhile taking a few minutes to look at the IPCC reports.

The most brief and to the point is the Summary for Policy Makers (SPM) that accompanies the fourth Assessment Report. You can find the summary at www.ipcc.ch/ipccreports/ar4-syr.htm. If you have time, the full report is also available at this site.

Open the SPM and look at the first page of text, then look at the first figure, SPM1 (reproduced here). Look at this figure carefully and answer the following questions:

1. What is the subject of each graph? Why are all three shown together?
2. Carefully read the caption. What does the area between the blue lines represent? Why are the blue lines shown in this report?
3. The left axis for all three graphs shows the difference between each year's observations and an average value. What values are averaged?
4. What do the blue lines represent? In the third graph, what is the value of the blue line, in million km^2, for the most recent year shown? Approximately what year had the lowest value shown? What does a decline in this graph represent on the ground?
5. Why is the trend in the snow cover graph less steep than the trends in the other two graphs?
6. Nearly every page of the IPCC report has graphs that show quite interesting details when you take the time to look at them. Choose two other graphs in the SPM document and explain the main messages they give. See if you can explain them clearly enough to communicate the main idea to a friend or family member. Have different students select different graphs and explain them to the class.

Changes in temperature, sea level and Northern Hemisphere snow cover



See the evidence: view the IPCC report at www.ipcc.ch/graphics/graphics/syr/spml.jpg.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham12e. You will find additional practice quizzes and case studies, flashcards, regional examples, placemarks for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.