



The Changing Climate

CHAPTER

7

Chapter Outline and Learning Goals

7.1 The Climate System

- ⊙ Differentiate between weather and climate and distinguish between climate forcings and climate feedbacks.

7.2 Climate Trends, Cycles, and Anomalies

- ⊙ Explain the factors that cause climate to change and explain how scientists investigate ancient climates.

7.3 Carbon and Climate

- ⊙ Compare the long-term and short-term carbon cycles and describe the role of human activity in changing those cycles.

7.4 Climate at the Crossroads

- ⊙ Weigh the evidence of an anthropogenic greenhouse effect in the atmosphere and describe its consequences.

7.5 Geographic Perspectives: Fixing Climate: The 2-Degree Limit

- ⊙ Assess the urgency of addressing climate change and different approaches to tackling the issue.



The methane bubbles in this photo are trapped in ice in Abraham Lake in the foothills of the Canadian Rockies in Alberta. Across the Northern Hemisphere, high-altitude lakes like Abraham are warming due to climate change. As a result, natural bacteria (called *methanogens*) that live in the sediments and produce methane are becoming more active. The methane the bacteria produce bubbles up through the water and freezes when it makes contact with colder water near the surface. The increased activity of methanogens is a major concern because methane is a very potent greenhouse gas that warms the atmosphere.

(Victor Liu, www.victorliuphotography.com)

To learn more about the structure of the atmosphere, see Section 1.4.

THE HUMAN SPHERE Nuisance Flooding

Some roads running through low-lying stretches of the East Coast are now almost routinely disappearing beneath 1 to 2 feet of seawater due to nuisance flooding (**Figure 7.1**).

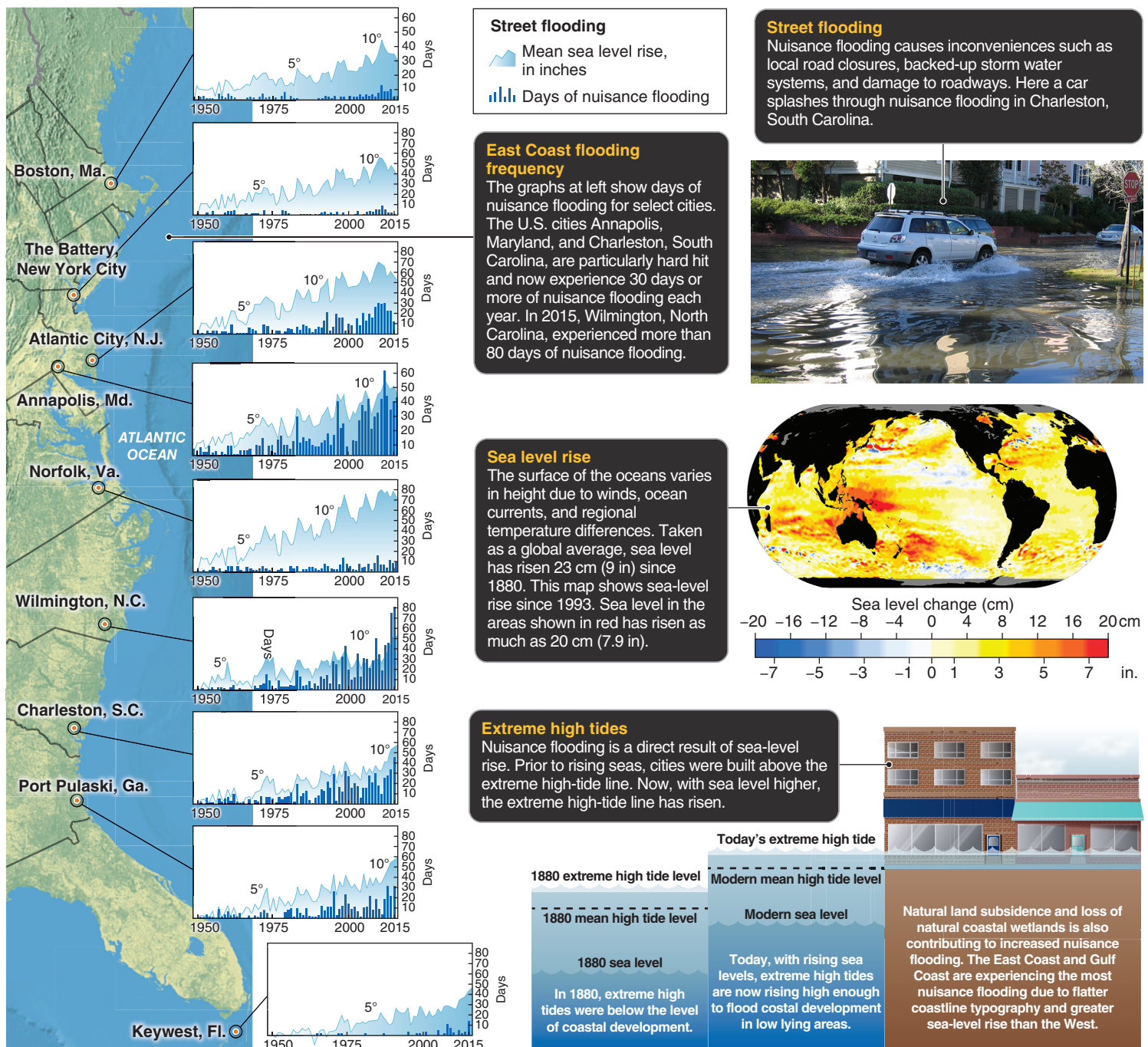
Nuisance flooding, also called “sunny-day flooding,” results when extreme high tides inundate low-lying coastal areas. Nuisance flooding events are increasing as sea level rises around the globe. Since 1880 mean global sea level has risen 23 cm (9 in),

and when the tide is unusually high, nuisance flooding may result. By the end of this century, global sea level is expected to be 1 to 2 m (3.3 to 6.6 ft) higher than today. By that time coastal flooding will no longer be merely a nuisance; it will be a major threat to low-lying coastal development.

Web Map

Sea Level Rise

Available at
www.saplinglearning.com



7.1 The Climate System

© Differentiate between weather and climate and distinguish between climate forcings and climate feedbacks.

Earth does not have just one type of climate. It has dozens—equatorial rainforest, dry interior desert, frozen tundra, grassland—all of which are examples of different vegetation zones resulting from different climate types. Several systems are used to classify Earth's many types of climates. The system we use in *Living Physical Geography* is the Köppen climate classification system. The Köppen (pronounced KER-puhn) system is presented in Section 9.1, in the context of global vegetation patterns. The emphasis in this chapter is on the average state of Earth's climate as a whole and how it changes naturally and due to human activity.

What Is the Difference between Weather and Climate?

Weather and climate are not the same. One way to understand the difference is to think of the expression “Climate is what you expect, but weather is what you get.” **Climate** is the long-term average of weather and the average frequency of extreme weather events. It is often calculated as an average of the previous 30 years of weather. For example, the average temperature or precipitation for a city can be calculated by averaging the past 30 years of temperature or precipitation data. **Weather** is the state of the atmosphere at any given moment and comprises ever-changing events on time scales ranging from minutes to weeks. Sunshine, rain showers, heat waves, thunderstorms, and clouds all are aspects of the weather.

Table 7.1 summarizes events that represent weather and climate. These events occur along a time continuum ranging from hours to tens of millions of years.

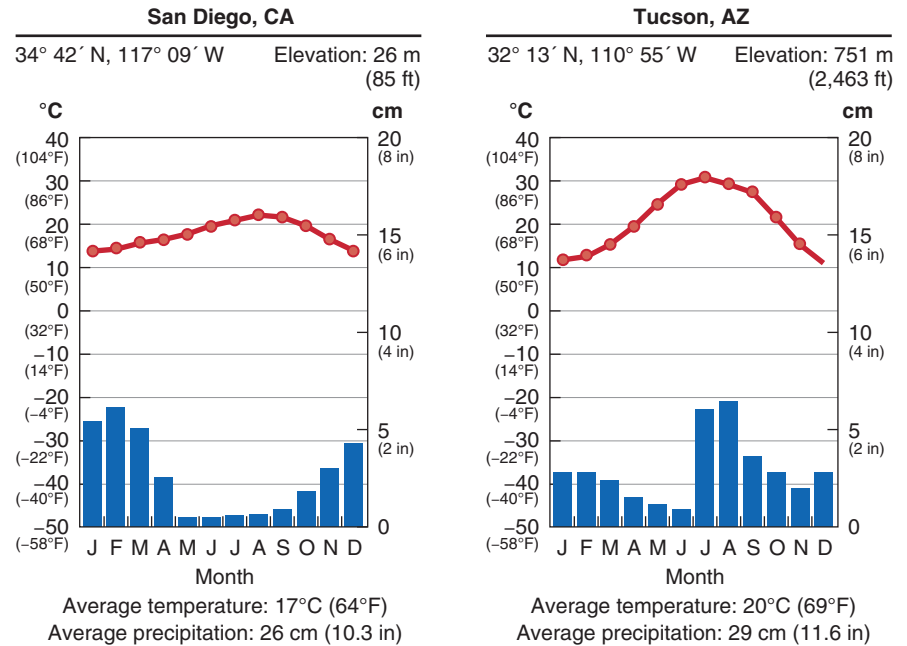


Figure 7.2 Climate diagrams for San Diego and Tucson. Although average annual temperatures and amounts of precipitation for these two cities are similar, the climate diagrams, which show average monthly temperature (red line) and precipitation (blue bars), reveal that their climates are quite different.

Weather and climate, while different, are related. Long-term weather observations such as temperature, precipitation, wind, and humidity are averaged to represent the climate of a given region. Simple annual averages of temperature and precipitation, however, do not fully describe the climate of a region. Take, for example, the average annual temperature and precipitation for San Diego, California, and Tucson, Arizona (**Figure 7.2**). Judging by their annual averages, these two cities appear to have similar climates—but they do not. Remember that climate also includes the frequency of extreme events. For example, much of Tucson's rainfall comes from thunderstorms in July and August. In contrast, San Diego gets winter precipitation from midlatitude

Table 7.1 Weather and Climate

PHENOMENA	TEMPORAL SCALE	WEATHER OR CLIMATE?
Cloudiness, rain shower, rainbow, sea breeze tornado	Minutes to hours	Weather
Night-and-day temperature difference	Days	Weather
Hurricane, midlatitude cyclone	Weeks	Weather
Winter, hurricane season, drought	Months	Climate
Asian monsoon	1 year	Climate
El Niño and La Niña	1 year or more	Climate
Younger Dryas*	1,000 to 10,000 years	Climate
Quaternary* glacial and interglacial cycles	10,000 to 1,000,000 years	Climate
Cenozoic* cooling	Millions of years	Climate

*These terms are defined in Section 7.2.

cyclones and almost no summer rain. Tucson also has a greater annual temperature range, with colder winters and hotter summers, than San Diego. Hard freezes and snow in winter are extremely rare in San Diego, but below-freezing winter temperatures do sometimes occur in Tucson.

Climate Change

Climate change occurs when the long-term average of any given meteorological variable—such as temperature or precipitation or the frequency of hurricanes—changes. Individual extreme weather events do not change the long-term average. Think of putting a single drop of water in a glass half-filled with water. One drop does not change the water level. But if enough drops are added, the water level gradually rises. Similarly, although a single weather event typically does not change the long-term average, if enough extreme weather events occur, the climate changes.

In recent years, weather stations, orbiting satellites, and ocean buoys have recorded innumerable extreme events, such as record-breaking heat waves and warm ocean water. Collectively, these extreme events are changing the long-term average. The official average global temperature record goes back to 1880. Since then the average temperature of the lower atmosphere has increased 0.99°C (1.78°F). Similarly, the surface of the oceans has warmed by about 0.56°C (1°F) in the past century. These gradual temperature trends in the atmosphere and oceans are climate change.

One question that frequently comes up is whether a single extreme event, such as Hurricane Irma, which caused widespread damage throughout most of Florida in 2017, was caused by climate change. Scientists know with certainty that the long-term average number of heat waves worldwide is increasing. The “extra” heat waves are a result of Earth’s changing atmosphere. Yet separating the heat waves or storm events that would have occurred without global temperature change from those that were caused by increased atmospheric temperatures is scientifically challenging. Every now and then, however, natural events that occur are so far outside the normal climate system’s behavior that they leave no doubt that Earth’s climate is changing right before our eyes. The **Picture This** feature on the following page discusses one such event.

Climate Forcing and Feedbacks

Climate is a result of the movement of energy and matter between Earth’s physical systems: the atmosphere, biosphere, lithosphere, hydrosphere, and cryosphere (introduced in Section 1.3). Recall that the cryosphere is the frozen portion of the hydrosphere, which includes glaciers and sea

ice. Long-distance connections between Earth’s different physical systems in different geographic areas are called *climate teleconnections*. El Niño’s wide reach (see Section 5.4) is a good example of the role of such long-distance connections.

Earth’s climate is controlled by two broad sets of factors. The factors that operate outside of and are independent of the climate system are **climate forcing factors**. The factors that arise within the climate system and are changed by the climate system are climate feedbacks (see Section 1.3).

The Sun is an example of a climate forcing factor. If the Sun it were to shine more intensely, it would force climate into a warmer state through *solar forcing*. Similarly, *volcanic forcing* may occur if a volcano erupts aerosols into the stratosphere. These aerosols may reflect sunlight and cool the planet’s surface for a year or two. The Sun and volcanoes, like all other climate forcing factors, are not affected by changes in climate.

In contrast to climate forcing factors, climate feedbacks involve interacting parts of the climate system that affect one another and are strongly affected by climate. Recall from Section 1.3 that negative feedbacks maintain a system’s stability and that positive feedbacks destabilize a system. There are many feedbacks in the climate system, some of which can support climate stability and others that can destabilize the climate system and cause climate change.

An example of a destabilizing positive feedback in the climate system is the **ice–albedo positive feedback**. Recall from Section 3.3 that Earth’s surface albedo varies considerably from region to region; surfaces with a low albedo absorb more solar energy than surfaces with a high albedo. When the temperature of the atmosphere increases, more snow and ice are melted. Compared to snow and ice, bare ground and ice-free water have a lower albedo and absorb more solar energy. As more bare ground and ice-free water are exposed, more warming occurs, creating a positive feedback loop (**Figure 7.3**).

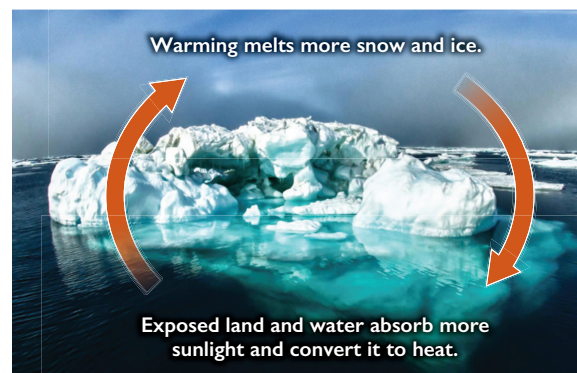
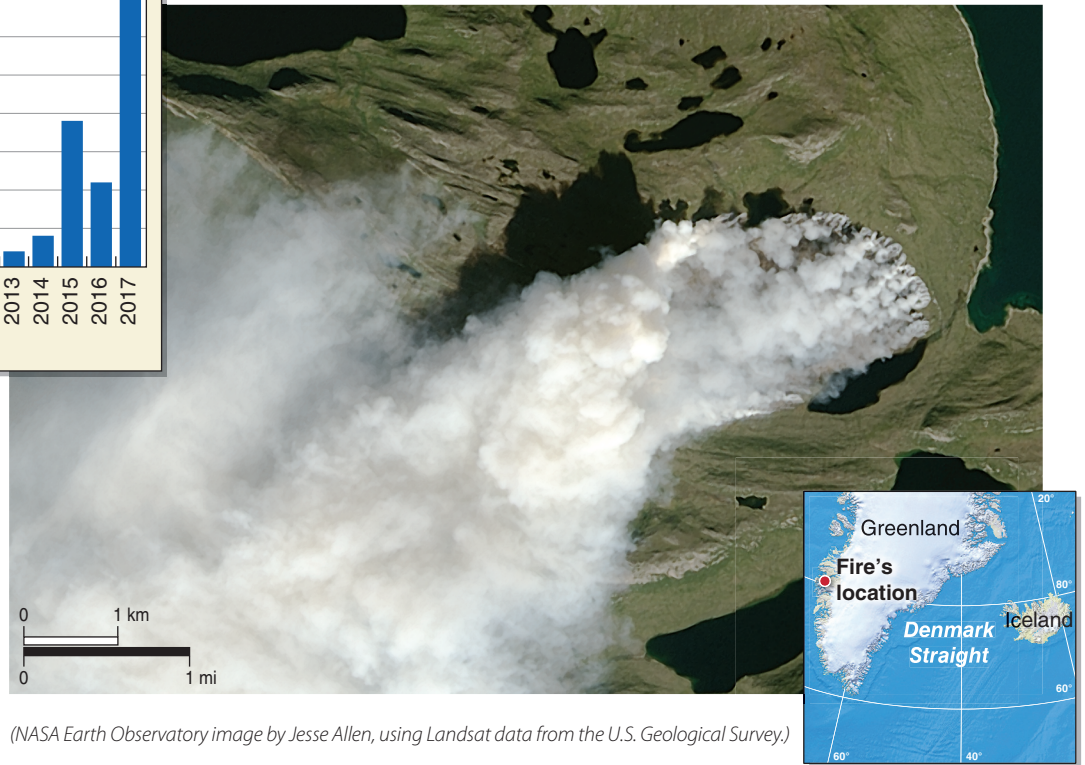
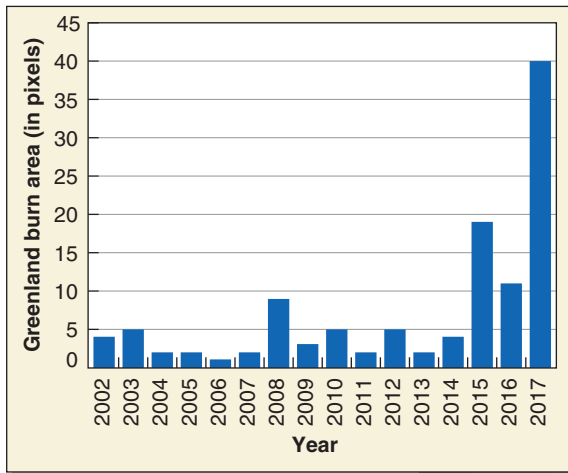


Figure 7.3 Positive feedback loop. (NOAA)

Picture This Greenland Burning



(NASA Earth Observatory image by Jesse Allen, using Landsat data from the U.S. Geological Survey.)

Scientists had never seen anything like it before. On July 31, 2017, satellites detected a large wildfire on the Greenland tundra that eventually burned 23 km² (9 mi²). This image, captured by Landsat 8, shows smoke from the fire on August 3, 2017. Over 80% of Greenland is covered by an ice sheet that is up to 3 km (2 mi) thick. Along the margins of the ice sheet, cold, wind-swept tundra vegetation is covered with snow for all but a few months of the year. Wildfires there are rare, and when they have burned in the past, they have always been small and short-lived. But the Arctic is warming at more than twice the rate of the middle and low latitudes, and an unusually warm and dry spell in 2017 in eastern Greenland created conditions that led to this surprising fire. Given that no thunderstorms

were detected in the area, the Greenland fire was likely caused by a campfire.

NASA's Aqua satellite has tracked fires in Greenland since 2000. Its data (inset graph) show that fire activity there is on the rise. Because of climate change, high-latitude fire activity across the Northern Hemisphere is now greater than at any other time in the past 10,000 years.

Consider This

1. Why was the Greenland fire so significant, even though it was small compared to fires that occur at lower latitudes?
2. Given what you know about albedo (see Section 3.3), if fire activity increases in Greenland, what will happen to Greenland's albedo? How could this affect the ice sheet?

The ice–albedo positive feedback destabilizes the climate system and causes climate change by enhancing the warming trend that was already taking place. But the ice–albedo positive feedback can cause cooling as well. If, for whatever reason, there were a cooling trend in Earth's atmosphere,

the ice–albedo positive feedback would enhance that cooling trend because more snow and ice would reflect more sunlight, resulting in further cooling. This happened 650 million years ago, creating a “Snowball Earth” state, with even the tropical oceans covered in ice.

In addition, feedbacks often trigger other feedbacks that accelerate the initial change. For example, warming temperatures increase the number of forest wildfires. Burning vegetation releases CO_2 , which enhances the preexisting warming. This is the *wildfire-carbon feedback*. Similarly, extensive frozen soils called *permafrost soils* are typically common at high latitudes, such as in Siberia and Canada's Northern Territories. But in many places permafrost is now thawing and releasing CO_2 and methane (CH_4) because methane-producing bacteria become more active as the soils warm. Methane is a much more potent (25 times more potent) greenhouse gas than CO_2 . The release of these greenhouse gases from thawing permafrost enhances the warming trend that is already under way. This is the *permafrost-carbon feedback*.

But positive climate feedbacks do not go on forever. They may be kept in check by other positive feedbacks pushing the system in the opposite direction. They can also be slowed by negative feedbacks that stabilize a changing system. We will return to the important role of climate forcing factors and feedbacks as we move through the remainder of this chapter.

7.2 Climate Trends, Cycles, and Anomalies

🕒 Explain the factors that cause climate to change and explain how scientists investigate ancient climates.

Earth's climate continually changes. The climate that we are experiencing today only developed about 10,000 years ago. The time our current climate has been in existence has been a mere snapshot in Earth's 4.6-billion-year history. On long-term time scales of millions of years,

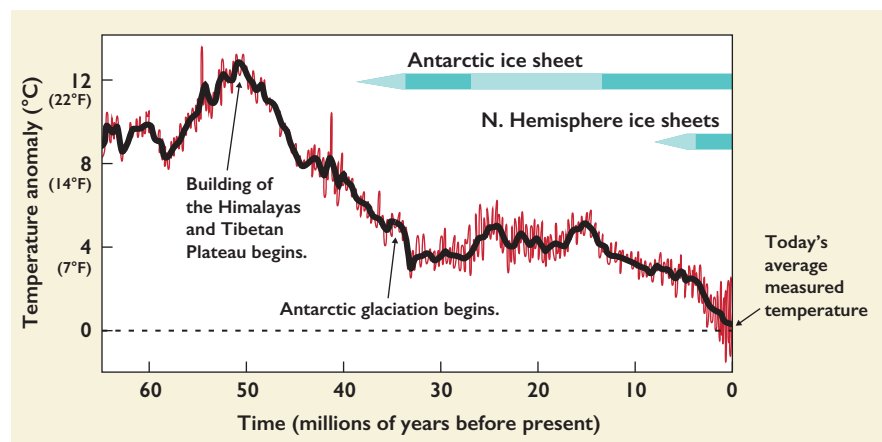
profound climate changes have stressed life on the planet and have even caused *mass extinction events*, in which over 75% of Earth's species went extinct. Smaller fluctuations of climate on short-term scales of hundreds and thousands of years are continually in motion. To see why climate changes and understand the context of what is happening to climate today, it is essential to examine the past. We can learn more about Earth's climate history by examining three natural modes of change: long-term trends, repeating cycles, and unpredictable anomalies.

Climate Trends: A Long, Slow Cooling

Earth's long history is divided into geologic time periods (see Section 12.2). One such period is the Cenozoic era. The **Cenozoic era** (or Cenozoic; pronounced see-no-ZO-ic) began 66 million years ago. It began when a large asteroid struck what is today the Yucatán Peninsula of Mexico, causing some 75% of life on Earth to go extinct—including the dinosaurs. Early in the Cenozoic, about 55 million years ago, the average global temperature was about 12°C (22°F) warmer than it is today. There was no ice at either of the poles. Atmospheric CO_2 concentrations were above 1,000 ppm, far higher than the present concentration of 408 ppm. (Recall from Section 2.1 that atmospheric carbon dioxide concentration is expressed in *parts per million*, or *ppm*.) After this warm period a long, slow cooling trend set in (**Figure 7.4**).

The building and uplift of the Tibetan Plateau and the Himalayas are the leading explanation for the Cenozoic cooling trend. Gradual weathering and erosion of the uplifting mountain range caused CO_2 in the atmosphere to bond with other minerals that became dissolved in rivers. As the rivers flowed to the ocean the minerals that were dissolved in them were deposited and stored as sediments and rocks on the ocean floor. The Cenozoic cooling trend gradually progressed as this process removed CO_2

Figure 7.4 Cenozoic cooling trend. The atmospheric temperature has dropped steadily since the early Cenozoic. Temperatures are given as anomalies above or below today's average, defined as 0°C (32°C). The cooling trend started when India began colliding with Asia, forming the Himalayas and Tibetan Plateau. The Antarctic ice sheet formed by about 35 million years ago, and the Greenland ice sheet (and other ice sheets in the Northern Hemisphere that are now gone) formed by about 6 million years ago.



from the atmosphere. This process is still unfolding, and weathering of the Himalayas is still drawing CO₂ out of the atmosphere. In the short-term, however, CO₂ emissions from human activity are far surpassing the removal of atmospheric CO₂ through weathering.

Climate Cycles: A Climate Roller Coaster

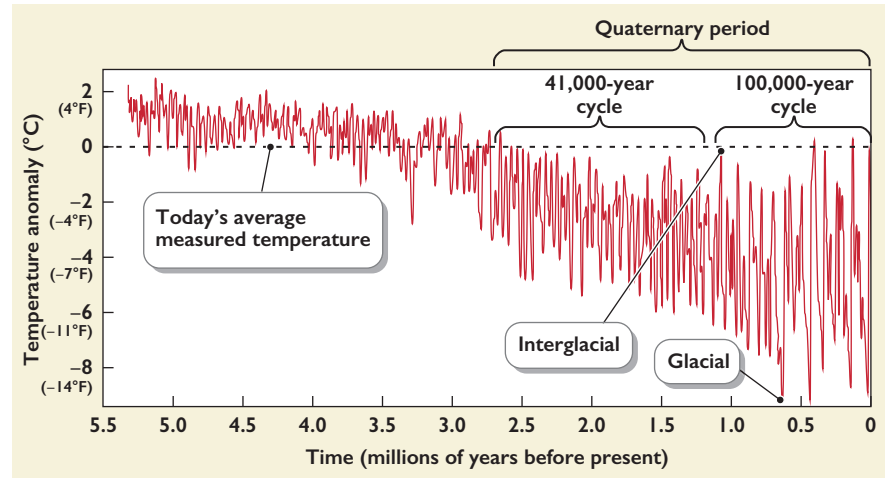
By 2.6 million years ago, as the Cenozoic became progressively colder, ice sheets began growing in northern Europe and North America. Scientists refer to this period of ice growth over Europe and North America as the **Quaternary period** ice age (or Quaternary; pronounced kwa-TER-nery). We are still in the Quaternary today. During the Quaternary, the climate has experienced a series of up-and-down swings like a roller coaster, cycling back and forth between cold glacial periods and warm interglacial periods some 22 times.

Glacial and Interglacial Periods

A **glacial period** (or *stadial*) is an interval of cold climate within the Quaternary ice age. An **interglacial period** (or *interstadial*) is an interval of warm climate that occurs between glacial periods. Between 2.6 million and 1 million years ago, swings between warm and cool climates occurred on a 41,000-year cycle. Since about 1 million years ago, glacial periods have lasted roughly 90,000 years, followed by interglacial periods lasting about 10,000 years (**Figure 7.5**).

Geologic time is separated into eras, which are subdivided into periods, which are in turn subdivided into epochs. We are currently in a warm interglacial called the **Holocene epoch** (pronounced HOL-o-seen). The Holocene, which began 11,700 years ago and continues today, is Earth's most recent interglacial. The Holocene is nested within the larger Quaternary period ice age, which in turn is nested within the larger Cenozoic era, which began 66 million years ago; we are currently in the Cenozoic Era, the Quaternary period, and the Holocene epoch (**Table 7.2**). Within the Quaternary as a whole, the Holocene has been a period of unusually stable climate. The

Figure 7.5 Quaternary temperature cycles. Climate swings occurred on a 41,000-year cycle before about 1 million years ago and then transitioned to a 100,000-year cycle. Scientists are uncertain why the transition to a 100,000-year cycle occurred.



average length of warm periods over the past million years has been roughly 10,000 years, which means we are likely nearing the end of the Holocene interglacial. Following this same cyclical pattern, in the next few thousand years, Earth's climate should enter a glacial cooling trend that will last some 90,000 years.

Why has climate cycled back and forth between warm interglacial and cold glacial conditions about 22 times during the past 2.6 million years? The first person to contribute to our understanding of this phenomenon was the largely self-educated Scottish scientist James Croll (1821–1890). Interestingly, Croll worked as a janitor while he was developing his climate theory. He first conceived the idea that changes in Earth's orbit around the Sun could produce cold glacial periods. This idea was further developed and mathematically refined by the Serbian astrophysicist Milutin Milankovitch (1879–1958).

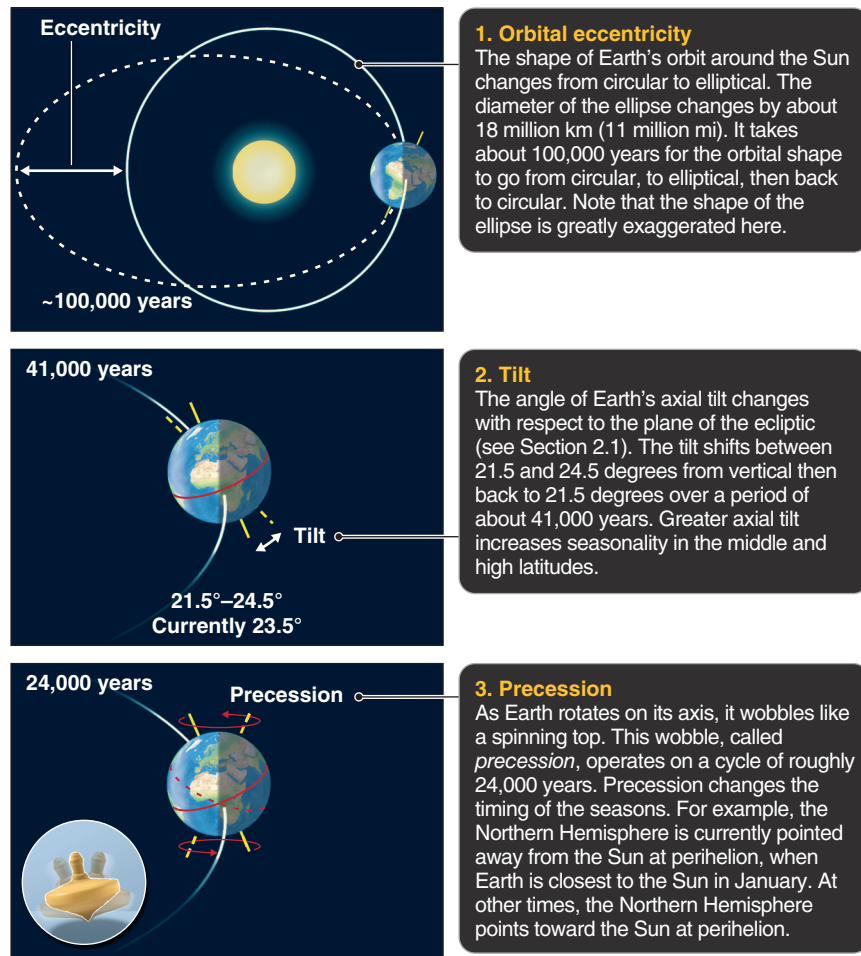
Milankovitch Cycles

Milankovitch identified three periodic changes in Earth's orbital relationship to the Sun that led

Table 7.2 Current Geologic Time Periods

	WHEN IT BEGAN	WHY IT BEGAN	CLIMATE CHARACTERISTICS
Holocene epoch	11,700 years ago	Beginning of the current interglacial period	Warm and stable interglacial climate
Quaternary period	2.6 million years ago	Beginning of the growth of ice sheets in North America and Europe	Alternating between cold glacial and warm interglacial periods about 22 times
Cenozoic era	66 million years ago	Large asteroid impact in eastern Mexico, extinguished 75% of life	Gradual cooling trend beginning 55 million years ago

Figure 7.6 Milankovitch Cycles. Milankovitch cycles create glacial and interglacial periods.



Animation

Milankovitch Cycles

Available at
www.saplinglearning.com



to changes in the timing and distribution of solar heating across Earth's surface (**Figure 7.6**). He asserted that these small changes in Earth–Sun orbital geometry, now called **Milankovitch cycles**, resulted in Quaternary glacial and interglacial cycles. Milankovitch developed a mathematical model that predicted climate cycles about every 100,000 years. His work went unrecognized for 50 years, until the mid-1970s, when new data from marine sediments led the scientific community to embrace his important theory.

Changing Earth–Sun orbital geometry is a process that operates outside, and is unaffected by, the climate system. Milankovitch cycles, therefore, constitute a climate forcing factor, referred to as *orbital forcing*.

Milankovitch cycles alter the intensity of sunlight over the seasons, but the Sun's energy output does not change significantly. The most important aspect of orbital forcing is that when it cools the Northern Hemisphere in summer (so that snow

and ice do not melt), snow accumulates and forms continental ice sheets. Ice sheets can only grow over land. Cooling the Southern Hemisphere summer cannot trigger ice sheet growth there because there is not enough land at mid and high latitudes where ice sheets develop. Internal feedbacks are important in amplifying the climate changes forced by Milankovitch cycles. As the ice sheets grow, the ice–albedo positive feedback causes further cooling. Glacial periods occur when the orbital distance from the Sun is greatest in the Northern Hemisphere summer and axial tilt is at a minimum.

Climate Anomalies: Unexpected Events

The pattern of climate change is like a layer cake. The bottom, foundation, layer is the long-term Cenozoic cooling trend. On top of that is a layer of the Milankovitch cycles, orbital forcing, and feedbacks. On top of that layer are unpredictable climate anomalies. The word *anomaly* refers to something that deviates from what is normal or expected. Anomalous climate events occur seemingly randomly through time and can be caused by both climate forcings and feedbacks. Changes in the Sun's output, volcanic eruptions, and changes in deep-ocean circulation are three examples of forcing and feedbacks that cause climate anomalies.

Changes in the Sun's Output

If **solar irradiance**—the Sun's total energy reaching Earth—were to increase, Earth would warm. If it decreased, Earth would cool. The amount of solar energy reaching Earth has been measured precisely since 1978 by satellites orbiting above the distorting effects of Earth's atmosphere. During this time, only small variations in the intensity of the Sun's output have been detected.

Sunspots are dark and relatively cool regions that migrate across the surface of the Sun. Approximately every 11 years, sunspot activity peaks. Dark sunspots are surrounded by regions of unusually high temperatures. As a result, increased sunspot numbers are correlated with a very slight overall increase in energy from the Sun reaching Earth. Ultraviolet radiation increases during high sunspot activity.

Although sunspots occur in cycles, not all of them have a discernible effect on Earth's climate. Instead of producing predictable temperature changes, these cycles produce unpredictable climate events. For example, low sunspot activity during a period 1645–1715, called the *Maunder Minimum*, coincided with a period of unusual cooling during the **Little Ice Age (LIA)**, a natural cooling period that extended from about 1350 to 1850 and was felt mostly in the Northern Hemisphere. High

Picture This The Little Ice Age and the Greenland Norse

The Scandinavian Norse (Vikings) settled coastal southern Greenland during the Medieval Warm Period in the 980s CE and developed a thriving society based on livestock rearing and trade. Perhaps as many as 5,000 Norse lived on Greenland at the peak of the settlement period. The Greenland colony was not self-sufficient. It was always too cold there to grow grain crops, and settlers relied on grain imports from northern Europe. The Greenland Norse traded polar bear hides, walrus ivory, butter, and wool for items they could not make or grow, such as grain, nails, wood, church bells, and wine.

Once the Little Ice Age set in, the growing summer sea ice made it increasingly difficult and dangerous to travel by boat from Greenland to trade with Europe. Worse, it became too cold on Greenland for settlers to grow food for themselves or for their livestock. The last written record of the Greenland Norse was a marriage document created in 1408. Sometime after that, their society collapsed, and they died or left Greenland. Those who could escape went to Iceland and mainland Europe, leaving behind gravesites and stone ruins such as the church of Hvalsey shown here.



(Danita Delimont/Getty Images)



Consider This

1. Compare the Greenland Norse to modern society in terms of their ability to anticipate upcoming changes in climate.
2. What are the similarities and differences between modern-day societies and climate change and the Greenland Norse and climate change?

sunspot activity may have triggered brief periods of warming, such as the **Medieval Warm Period (MWP)**, a naturally warm period that extended from about 950 to 1250 CE and was felt mostly in the Northern Hemisphere. The **Picture This** feature above discusses the LIA and MWP in the context of Norse settlers on Greenland.

Volcanic Eruptions

Large volcanic eruptions can cool Earth's surface temperature for 1 or 2 years. To cause cooling, ash and sulfur dioxide from the volcanic eruption must enter the stratosphere, where rainfall will not wash it out of the atmosphere. Only the largest volcanic eruptions are capable of spewing

material into the stratosphere. Sulfur dioxide from large volcanic eruptions combines with water to form reflective sulfuric acid droplets. These aerosols may remain suspended in the stratosphere for up to 5 years, where they reflect incoming sunlight, thereby cooling Earth's surface. In June 1991, Mount Pinatubo, in the Philippines, erupted, sending 10 km^3 (2.4 mi^3) of pulverized rock and ash into the upper atmosphere and causing climate cooling (**Figure 7.7** on the following page).

The eruption of Mount Tambora in Indonesia in 1815 was among the largest historical volcanic eruptions. It led to cold summers and failed crops in many regions of the world. It was so cold throughout northern Europe that

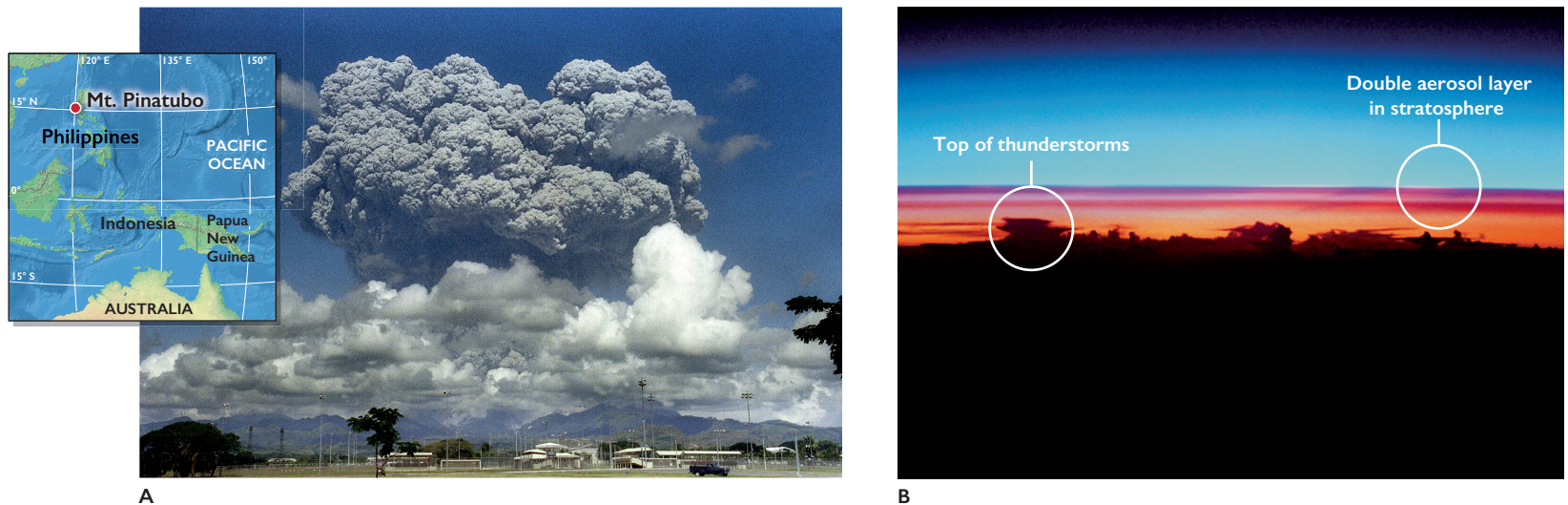


Figure 7.7 1991 Mount Pinatubo eruption. (A) The eruption column of Mount Pinatubo reached 32 km (20 mi) into the atmosphere. The resulting veil of ash and sulfuric acid droplets spread around the world within weeks and remained suspended in the stratosphere for over 5 years, causing up to 1.3°C (2.3°F) of cooling in some regions. (B) This photograph of the atmosphere's limb was taken in 1991 by astronauts aboard the space shuttle. The photo shows a double layer of volcanic aerosols in the stratosphere, high above the tops of thunderstorms, which terminate at the tropopause. (A. Arlan Naeg/AFP/Getty Images; B. NASA)

1816 was called “the year without a summer.” This event is explored further in Section 15.5. Volcanoes can also cause long-term trends of warming when they emit large quantities of CO₂ over time spans of hundreds of thousands to millions of years.

Changes in the Ocean Conveyor Belt

Before the 1980s, scientists thought that major shifts in climate happened smoothly and too

slowly for humans to directly perceive. In the 1980s, however, new data taken from ice cores indicated that climate can change in a matter of decades or less. Like a precariously balanced bucket that, with a little nudging, tips over, the climate system reaches “tipping points.” After these points, it may change quickly. This type of climate behavior is referred to as *nonlinear* because the initial changes in the system are slow at first and then accelerate as positive feedbacks take over and destabilize the system rapidly.

One example of nonlinear climate change is the **Younger Dryas**, a cold period that occurred between 12,900 and 11,600 years ago, just overlapping with the start of the Holocene, 11,700 years ago. (It was named after the cold-loving plant *Dryas octopetala*, also called mountain avens.) During this period, within a few decades or less, much of the Northern Hemisphere plunged into deep cold. Some places experienced colder temperatures than others. Ice cores retrieved from the summit of the Greenland ice sheet show that the average temperature there dropped about 15°C (27°F) and stayed low for about 1,300 years. **Figure 7.8** compares the Younger Dryas event with the relatively stable Holocene climate of the past 10,000 years.

What happened 12,900 years ago to cause temperatures to plunge so quickly in the Younger Dryas? There are several competing scientific

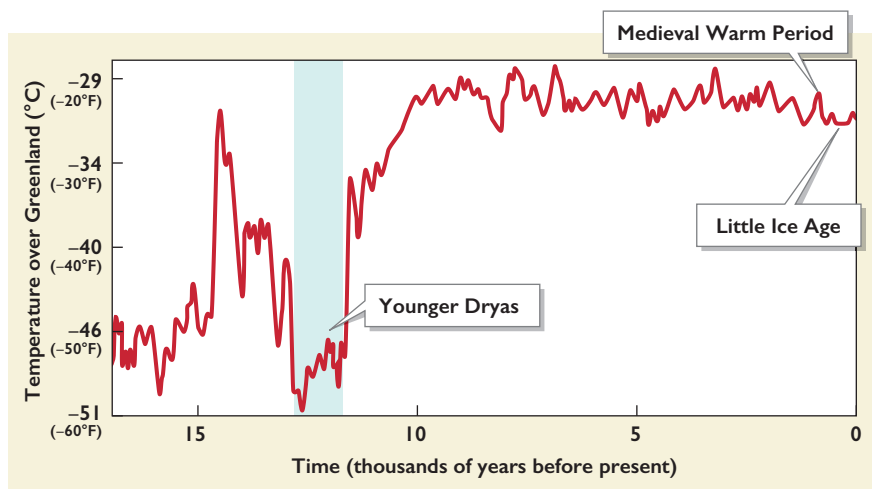
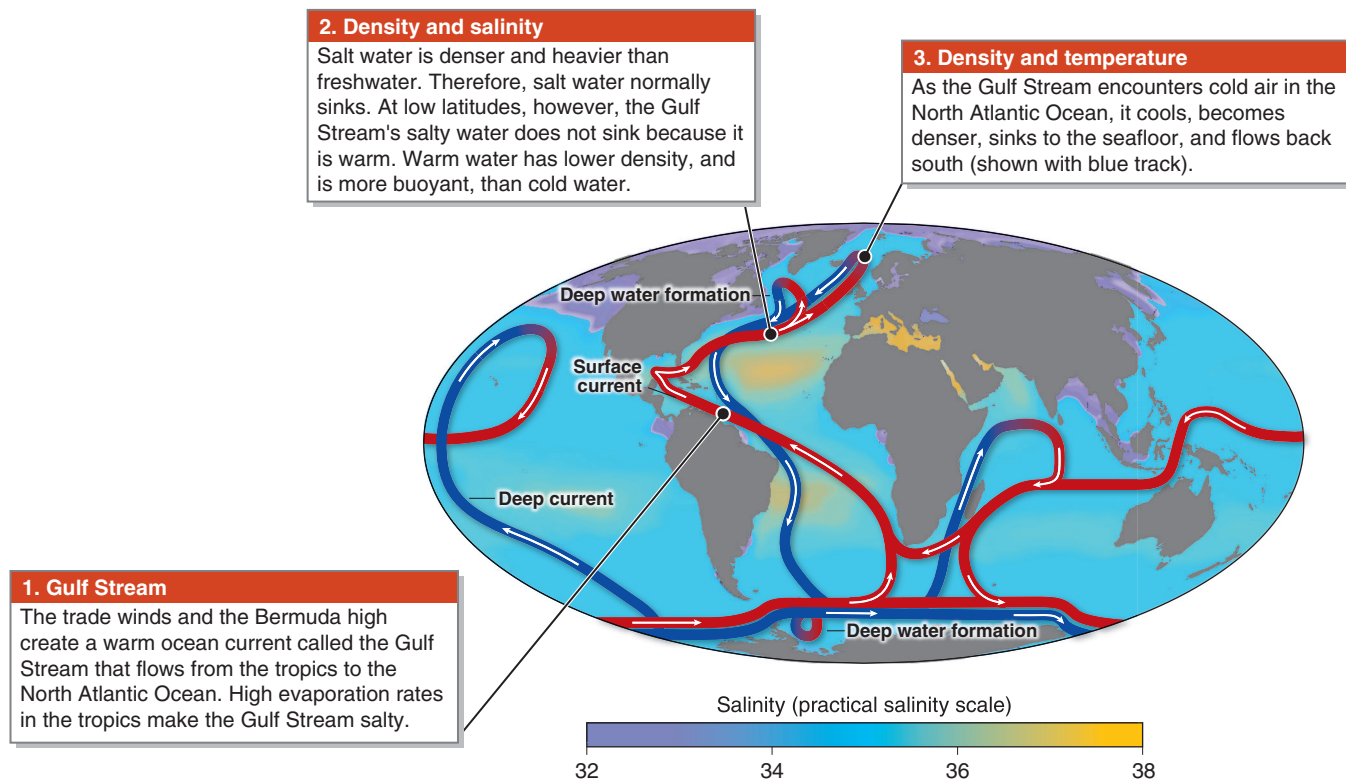


Figure 7.8 The Younger Dryas. The Younger Dryas cold period came and went abruptly. For comparison, the Medieval Warm Period and the Little Ice Age are also shown. Compared with the Younger Dryas, climate change in those events was insignificant.

Figure 7.9 The ocean conveyor belt system. The global system of ocean currents moves heat from the tropics to higher latitudes. (Map by Robert Simmon, adapted from the IPCC 2001 and Rahmstorf 2002)



ideas. One widely accepted explanation is that changes in the circulation of ocean currents caused it. Scientists think that an important part of Earth's climate system is the circulation of ocean water, which behaves something like a conveyor belt. At grocery stores, we often see conveyor belts that transport our groceries from near the cart to within easy reach of the cashier. The **ocean conveyor belt** (more technically referred to as the *Atlantic meridional overturning circulation* or *AMOC*) is the global system of surface and deep-ocean currents that transfers heat toward the poles. The ocean conveyor belt's flow depends on differences in the buoyancy of ocean water caused by differences in temperature and salinity. Colder, saltier water sinks to the depths and warmer, fresher water rises to the surface.

Figure 7.9 explains how this system works.

The Gulf Stream transports 25% of all global heat moving to higher latitudes. The faster the Gulf Stream flows, the more heat it delivers to the North Atlantic Ocean and to the atmosphere in the Northern Hemisphere. If the ocean conveyor belt system slows down or stops, the Northern Hemisphere gets colder. The ocean conveyor belt system greatly slowed or shut down entirely 12,900 years ago, plunging most of the Northern

Hemisphere into 1,300 years of frigid Younger Dryas climate. Once the Northern Hemisphere became cooler, the ice-albedo positive feedback maintained the Younger Dryas cooling that was initially triggered by changes in the ocean conveyor belt system.

Why would the ocean conveyor belt system slow or shut down? Evidence indicates that a massive influx of freshwater into either the North Atlantic Ocean or the Arctic Ocean forced the system to shut down. Why would freshwater shut down the system? Freshwater is more buoyant than salt water. If the Gulf Stream were freshened, it would become more buoyant and would no longer sink in the North Atlantic Ocean. This would slow down or stop the conveyor system altogether.

It would take a lot of freshwater to slow the ocean conveyor belt system. As **Figure 7.10** on the following page shows, that water probably came from the melting of the **Laurentide ice sheet**, the large ice sheet that covered much of North America during the most recent glacial period until about 12,000 years ago.

In April 2018, new research published in *Nature* found that during the last decade the conveyor system has been slowing down slightly.



Figure 7.10 Laurentide ice sheet. At its maximum extent 20,000 years ago, the Laurentide ice sheet covered much of Canada. As it melted in response to Milankovitch forcing, the meltwater flowed out the Saint Lawrence River, the Mississippi River, and the Mackenzie River, adding freshwater to the oceans. At times during the melting process, ice dams created huge inland lakes (such as those shown here in dark blue). Scientists hypothesize that ice dams broke repeatedly over time and released massive pulses of freshwater into the North Atlantic Ocean. The freshwater slowed or stopped the ocean conveyor belt system and caused cooling events such as the Younger Dryas.

This has resulted in a persistent cold patch of water in the North Atlantic just south of Greenland (see Figure 17.18B). Scientists expect that the cooling produced by changes in the ocean conveyor belt system will be very slight compared to the warming caused by increased greenhouse gases in the atmosphere due to human activity.

Reading the Past: Paleoclimatology

How do scientists know what Earth's climate was like many thousands of years ago? Earth's climate history is recorded in various natural archives, including growth rings in trees, glaciers, and ocean sediments.

Scientists who study **paleoclimates**, which are Earth's ancient climates, are *paleoclimatologists*. They analyze natural Earth materials that record environmental changes in layers that have been left undisturbed. By analyzing these materials, they reconstruct ancient environments (**Figure 7.11**).

7.3 Carbon and Climate

🎯 **Compare the long-term and short-term carbon cycles and describe the role of human activity in changing those cycles.**

Earth's climate system is strongly influenced by greenhouse gases in the atmosphere, particularly water vapor and carbon dioxide (see Table 2.2). Carbon dioxide has a particularly important influence today because human activities emit more of it than ever before, and its anthropogenic emissions are growing faster than those of any other greenhouse gas. Carbon dioxide is like a global thermostat that controls the temperature in a house. When carbon dioxide is increased, the atmosphere warms; when carbon dioxide is decreased, the atmosphere cools. The Cenozoic cooling trend, for example, was caused by a gradual decrease of carbon dioxide in the atmosphere. Similarly, past warm periods in Earth's history were caused by an increase in atmospheric carbon dioxide. The remainder of this chapter focuses on the role of carbon and carbon dioxide in changing Earth's climate.

Carbon atoms move among Earth's physical systems through the **carbon cycle**. When bonds form between a carbon atom and two oxygen atoms, a carbon dioxide molecule (CO_2) is formed. When these bonds are broken, the carbon atom is freed from the oxygen atoms. In this section, we consider both carbon atoms and carbon dioxide molecules as they move through the carbon cycle.

To better understand the role of carbon in Earth's physical system, we divide the carbon cycle into a *long-term carbon cycle* and a *short-term carbon cycle*. The long-term carbon cycle involves the movement of carbon into and out of the lithosphere and takes millions of years to unfold. The short-term carbon cycle involves the movement of carbon among the oceans, the atmosphere, and the biosphere over spans of time from minutes to a few thousand years. (Section 7.4 includes a more detailed description of the short-term carbon cycle.)

The Long-Term Carbon Cycle

About 99.9% of Earth's carbon (65,500 billion metric tons) is stored in the lithosphere, where it is bonded with other elements to form different materials, including many types of rocks and fossil fuels (coal, oil, and natural gas). Coal is the preserved remains of ancient terrestrial (land) plants, and petroleum oil is formed from the remains of ancient marine (ocean) plankton. Natural gas is formed and found with both coal and oil. The other 0.1% of Earth's carbon is found in the oceans, atmosphere, and biosphere. Carbon moves from the atmosphere, oceans, and biosphere into the lithosphere through

Figure 7.11 SCIENTIFIC INQUIRY: How do paleoclimatologists reconstruct ancient climates? Natural archives of information about Earth's past can be found in a wide range of environments. In each of the settings shown here, layers record the changing environmental conditions. Layers can be formed through biological growth, as in tree rings and corals; through the settling of material by gravity, as in lake sediments, marine sediments, and snow on glaciers; or through nonliving growth, such as mineral deposits in caves. Paleoclimatologists extract cores of these materials and analyze the layers to gain an understanding of past environments and how they change through time. (From top left to bottom right. Bruce Gervais; Hickerson/FGBNMS/NOAA; Lonnie G. Thompson, Byrd Polar Research Center, Ohio State University; Auscape/UiG/Getty Images; Rod Benson; William Crawford, IODP/TAMU; John Beck, IODP/TAMU)



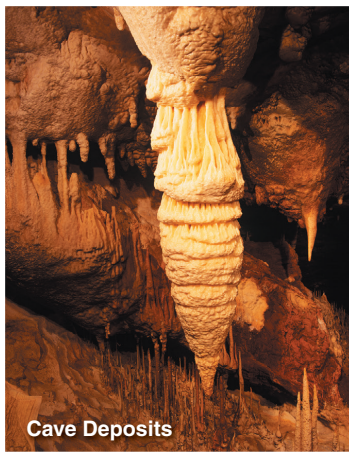
Tree rings



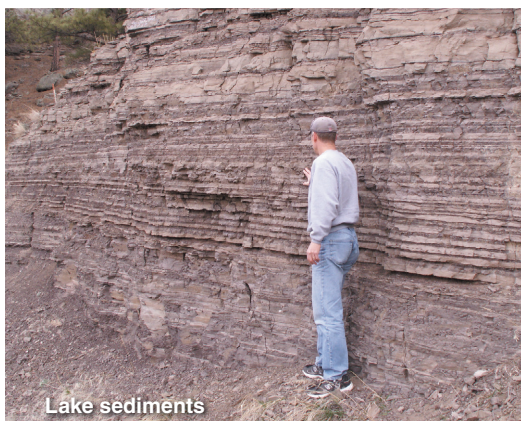
Corals



Glaciers



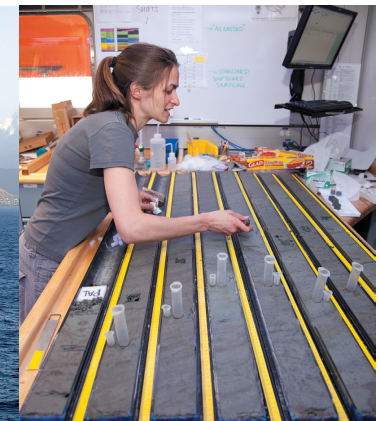
Cave Deposits



Lake sediments



Marine sediments



Temporal Resolution and Extent of Paleoclimate Records

MATERIAL	HOW FAR BACK IN YEARS?	TEMPORAL RESOLUTION
Tree rings	Thousands	Annual
Corals	Tens of thousands	Annual
Glaciers	Hundreds of thousands	Annual
Cave deposits	Hundreds of thousands	Decades
Lake sediments	Hundreds of thousands	Decades
Marine sediments	Millions	Centuries

Natural materials vary in how far back in time their records reach and in their *temporal resolution*: how focused in time the information is. Tree rings provide information for each year (annual resolution), while marine sediments provide information for increments of about 100 years or longer (centennial resolution).

weathering and erosion and through the burial and preservation of photosynthetic organisms on land and in the oceans. Carbon leaves the lithosphere and enters the atmosphere through volcanic eruptions and through the burning of fossil fuels.

Weathering and Erosion Remove Carbon from the Atmosphere

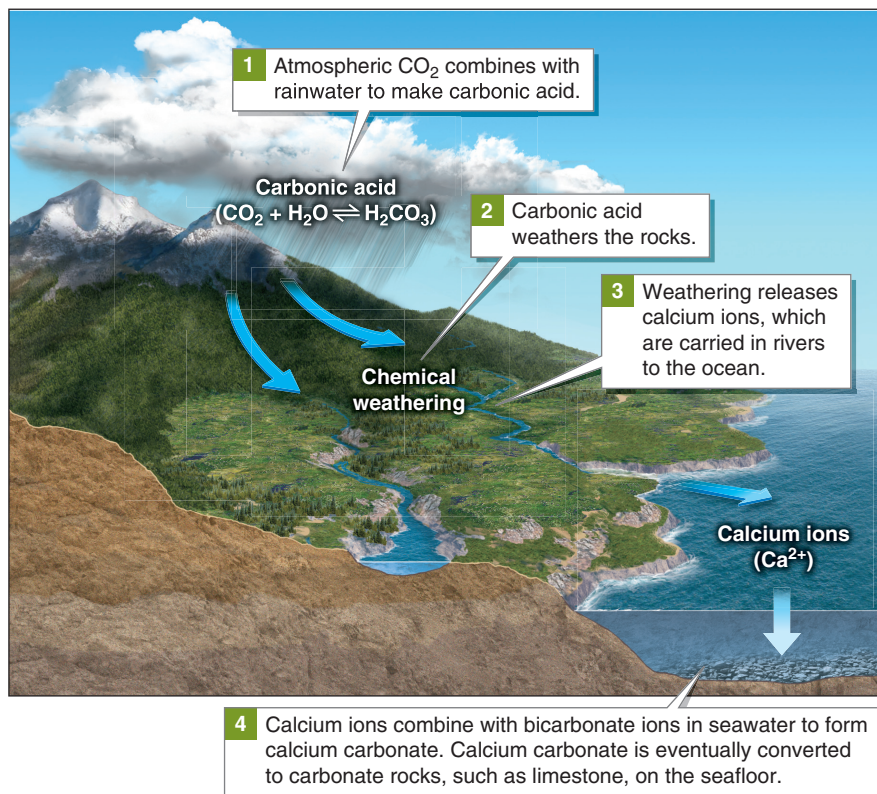
Carbon dioxide in the atmosphere combines with rainwater to form a weak acid called *carbonic acid* (H_2CO_3). Carbonic acid in rainwater slowly

dissolves the rocks over which it flows, through the process of *chemical weathering*. This process releases calcium ions that rivers carry to the oceans. *Ions* are atoms or molecules with electrical charges that readily react with other particles. Calcium ions combine with bicarbonate ions (HCO_3^-) in seawater to create chalky white *calcium carbonate* (CaCO_3) sediments, which are similar to the deposits that accumulate on faucets in homes with hard, mineral-rich water. Organisms such as corals and clams also build their shells from calcium carbonate ions, pulling carbon from seawater in the process. When they die, their shells form layers of sediments as well. Over time, these sediments and remnants of shells, cemented together, form *carbonate rocks* such as limestone, locking away immense reserves of carbon in long-term storage reservoirs in the lithosphere (Figure 7.12).

Photosynthesis Removes Carbon from the Atmosphere

The second way that carbon enters long-term storage reservoirs in the lithosphere is through photosynthetic organisms, which include plants, algae, and certain types of bacteria. These organisms convert the Sun's radiant energy to chemical energy through the process of photosynthesis.

Figure 7.12 Carbon transfer from the atmosphere to the lithosphere. This process of carbon removal from the atmosphere drove the long-term cooling trend of the Cenozoic era.



During photosynthesis, they absorb carbon dioxide from the atmosphere, split the oxygen from it, and store the resulting carbon in their tissues.

Normally, after these photosynthetic organisms die, they soon decompose. The carbon in their tissues recombines with oxygen in the atmosphere to make carbon dioxide again. Under certain *anaerobic* (oxygen-free) conditions, however, these organisms and the carbon in their tissues is preserved rather than decomposed.

Several hundred million years ago, microscopic photosynthetic marine algae and bacteria (called *phytoplankton*) and terrestrial forests grew, died, and did not decompose. At that time, Earth was much warmer, and climate favored their preservation. Their carbon-rich remains accumulated and were preserved in marine sediments on the seafloor or in peat wetlands on land. Over millions of years, the preservation of these organisms gradually transferred carbon from the atmosphere and oceans into long-term storage in the lithosphere. This process of transferring carbon from the atmosphere to long-term storage in marine sediments is known as the *biological pump*. Today, the remains of these organisms are fossil fuels. As people burn them, the ancient carbon stored within them recombines with oxygen in the atmosphere and forms carbon dioxide.

The Short-Term Carbon Cycle

The short-term carbon cycle involves the movement of carbon among the oceans, the atmosphere, and the biosphere on time scales ranging from minutes to thousands of years. The oceans store the vast majority, 91%, of the carbon that moves through the short-term carbon cycle. The biosphere stores 7%, and the atmosphere stores only 2% of the carbon in the short-term carbon cycle.

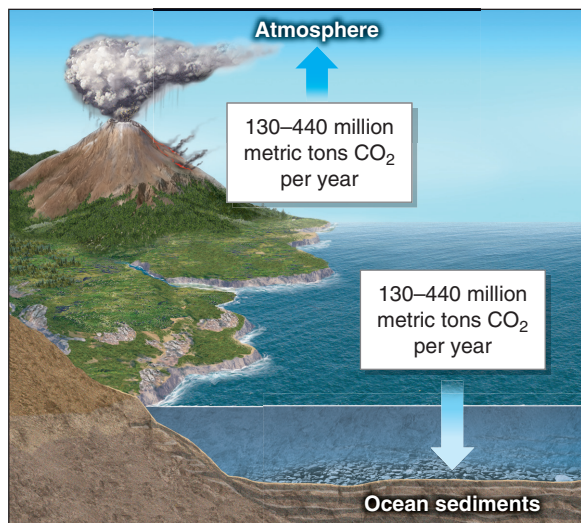
The oceans readily absorb carbon dioxide from the atmosphere. About 50% of the carbon humans have put into the atmosphere by burning fossil fuels since the Industrial Revolution has been absorbed out of the atmosphere by the oceans.

Carbon does not take long to move between the biosphere, atmosphere, and oceans. For example, each breath we exhale moves carbon from the biosphere (our bodies) to the atmosphere. Whenever an organism dies and decomposes, bacteria recycle the carbon in its body back into the atmosphere and the soil, where that carbon becomes available to other organisms.

The Anthropogenic Carbon Cycle

During the 800,000 years before the Industrial Revolution, approximately the same amount of

Figure 7.13 Natural transfer of carbon dioxide between the lithosphere and the atmosphere. Each year volcanic activity moves about 130 to 440 million metric tons of CO_2 into the atmosphere. Chemical weathering of rocks moves about the same amount of CO_2 from the atmosphere to the lithosphere.



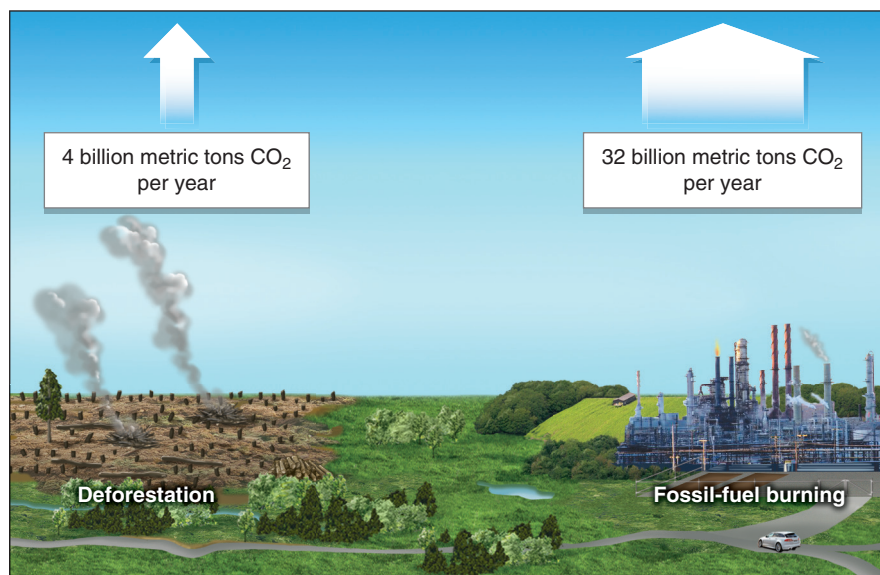
carbon that entered the atmosphere through volcanoes left the atmosphere through weathering of rocks (**Figure 7.13**). As a result, carbon dioxide levels in the atmosphere hovered around a steady state between 200 and 300 ppm.

During the *Industrial Revolution*, which began in roughly 1800, people first began burning large amounts of fossil fuels to run machines. Now human activity injects about 100 times more CO_2 into the atmosphere than all the world's volcanoes and other natural sources combined. In about 4 days, human activity emits as much CO_2 as an entire year's worth of natural emissions. By burning fossil fuels, people transfer carbon from long-term storage to the short-term carbon cycle. As **Figure 7.14** illustrates, fossil-fuel burning is the main human activity that adds CO_2 to the atmosphere, but deforestation and land-use changes also play a role.

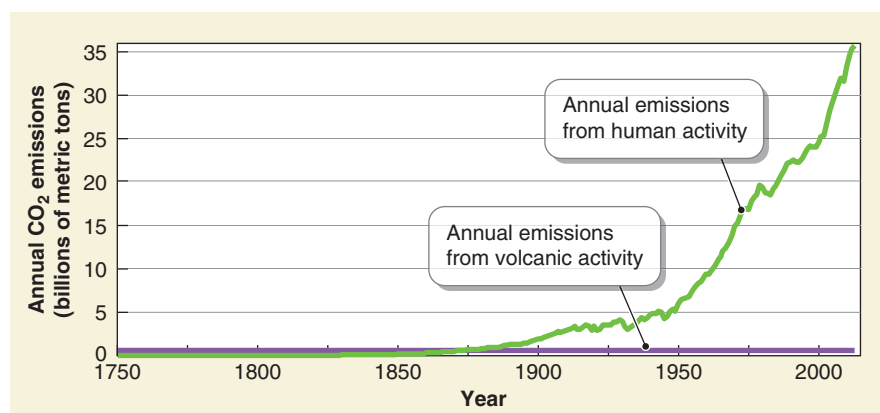
7.4 Climate at the Crossroads

🕒 **Weigh the evidence of an anthropogenic greenhouse effect in the atmosphere and describe its consequences.**

The transfer of carbon from long-term storage to the short-term carbon cycle has important implications for the climate system. Carbon dioxide in



A



B

Figure 7.14 Anthropogenic transfers of carbon dioxide to the atmosphere. (A) Human activity now adds 35 to 40 billion metric tons of CO_2 to the atmosphere each year. Deforestation adds about 4 billion metric tons of CO_2 to the atmosphere each year. Fossil-fuel burning adds about 32 billion metric tons of CO_2 to the atmosphere each year. (B) Here natural volcanic CO_2 emissions (purple) are graphed next to anthropogenic CO_2 emissions (green). Natural volcanic emissions remain stable, while anthropogenic emissions have grown with each passing year.

the atmosphere is a greenhouse gas and a climate forcing factor. It absorbs heat and increases the temperature of the atmosphere (see Section 3.3).

Human activity is increasing atmospheric CO_2 concentrations by over 2.5 ppm per year. Precise measurements of atmospheric CO_2 were begun by Charles Keeling in 1958 at Mauna Loa Observatory in Hawai'i. The observatory is far away from the effects of cities and pollution, and the measurements are taken upwind of any volcanic emissions.

Video

Following Carbon Dioxide Through the Atmosphere

Available at
www.saplinglearning.com



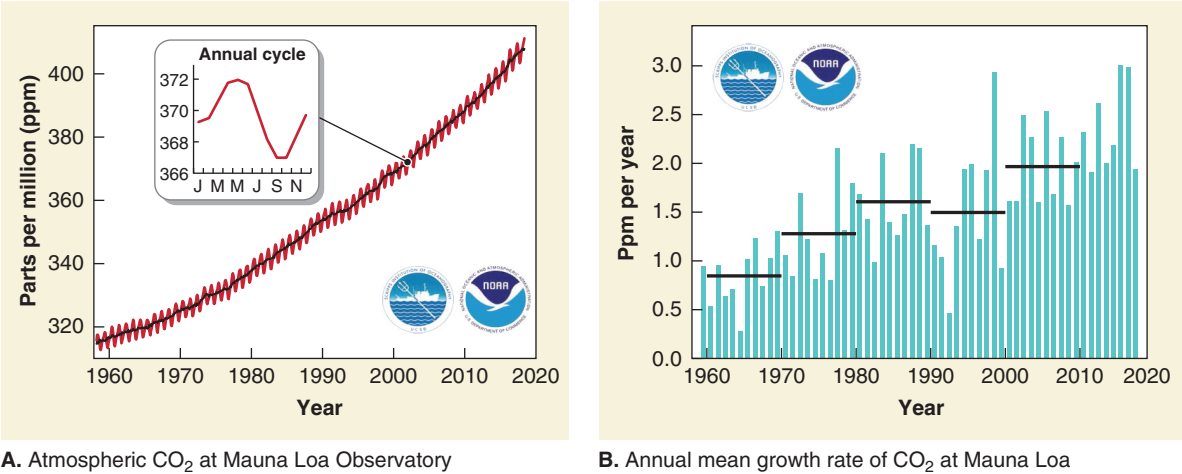
Animation

Anthropogenic Carbon Emissions

Available at
www.saplinglearning.com



Figure 7.15 Modern CO₂ concentrations. (A) The Keeling curve, shown here, graphs concentrations of CO₂ in the atmosphere since 1958. The red line is actual CO₂ measurements, which fluctuate with the seasons. In summer, values drop as plants grow and pull CO₂ from the atmosphere. In winter, values rise as plants lose their leaves, which decay and release stored carbon back into the atmosphere (inset graph). The black line is the annual average. (B) The rate of increase of atmospheric CO₂ concentrations is shown here. The black bars show the average annual rate of increase by decade. In the 1960s, CO₂ rose a little less than 1 ppm per year. By 2000–2010, the average annual rate of increase had doubled to 2 ppm per year. (Data from NOAA)



The **Keeling curve** is a graph showing the change in atmospheric CO₂ concentrations since 1958 (**Figure 7.15**).

But what were atmospheric CO₂ concentrations before 1958, when Keeling and other scientists began measuring them? To find out, scientists have analyzed air bubbles in ancient ice from the Greenland and Antarctic ice sheets (**Figure 7.16**). They have found that before 1800, CO₂ concentrations were much lower than they are today. Atmospheric CO₂ increased after societies began burning fossil fuels in large quantities.

Temperature and CO₂ always rise and fall together. Note that today’s CO₂ level is far higher in comparison with any levels seen during the past 800,000 years, and the speed at which CO₂ is rising today is unprecedented (**Figure 7.17**).

The causal relationship between atmospheric CO₂ and temperature is complex. Both influence each other. Rising temperature caused by orbital forcing increases atmospheric CO₂ because warmer oceans release stored CO₂. (Warm water holds less dissolved CO₂ than cold water.) Likewise, increased CO₂ in the atmosphere causes more warming through the greenhouse effect. Recent research of Antarctic ice cores suggests that, rather than one leading the other, CO₂ and temperature change together and affect one another synchronously.

The Warming Atmosphere

Today, human activities are inadvertently tinkering with Earth’s greenhouse gas–controlled thermostat. Natural atmospheric CO₂ concentrations never exceeded 300 ppm during the last 3 million years. In the past 150 years, CO₂ concentrations have risen sharply to over 400 ppm due to human activities. Human emissions of CO₂ and other greenhouse gases into the atmosphere are creating an anthropogenic greenhouse effect (see Section 3.3).

Carbon dioxide gas is not the only greenhouse gas produced by people. Methane, nitrous oxide, and halogenated gases are far more efficient at causing warming than CO₂ and, like CO₂, all of them are currently far above their historic natural levels. Carbon dioxide is the most important anthropogenic greenhouse gas, however, because human activities emit more of it than any other greenhouse gas. **Table 7.3** provides the

Table 7.3 Greenhouse Gas Sources		
	ANTHROPOGENIC	NATURAL
Carbon dioxide (CO ₂)	Burning fossil fuels (coal, oil, natural gas), deforestation, biomass fuel burning, fertilizers, cement production	Volcanic activity, vegetation decomposition
Methane (CH ₄)	Livestock, fossil-fuel mining, anaerobic agricultural fields, burning vegetation	Bacterial processes in wetlands, mammals, and termite mounds
Nitrous oxide (N ₂ O)	Fertilizers, wastewater, fossil fuels, industrial activity, vehicles	Soil bacterial processes
Halogenated gases (CFCs, HFCs)	Industrially manufactured for various uses	None

anthropogenic and natural sources of important greenhouse gases.

As CO₂ and other greenhouse gas concentrations increase, so does the global temperature. Each passing decade is warmer than the last. In recent years, record temperatures have become routine. The years 2014, 2015, and 2016 each set records as the hottest year to date, and the year 2017 tied 2015 as the world's second hottest year. In July 2015, China set an all-time high of 50.8°C (122.5°F); in May 2016, India's highest temperature reached 51°C (123.8°F); in June 2017, Iran recorded 54°C (129°F); and in July 2017, Spain reached 47.3°C (117.1°F). As these extreme high temperatures events become more frequent, they are changing the long-term average. Although there is year-to-year fluctuation, this trend of planetary heating began in the early 1900s (**Figure 7.18A** on the following page).

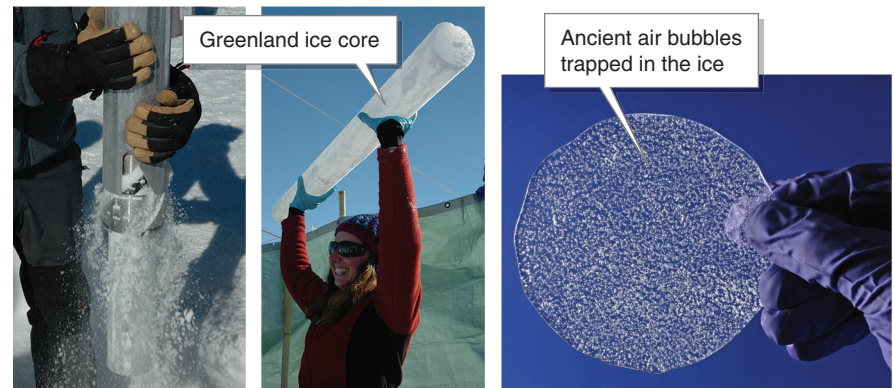
Earth's average surface air temperature in 2017 was 0.99°C (1.78°F) above the twentieth-century average, but the Arctic is warming at more than twice the rate of the rest of the world (**Figure 7.18B** on the following page). The ice-albedo positive feedback (see Figure 7.3) is creating nonlinear rates of warming at high latitudes, a process known as **Arctic amplification**—the tendency of high-latitude regions to warm faster than the rest of the planet. Recent studies also indicate that dark *soot*, black dust from fossil-fuel combustion at lower latitudes, is driving a significant portion of the warming in the Arctic. As soot settles on ice, it darkens the white surface and lowers the albedo of the ice. As a result, the ice absorbs more solar radiation, which in turn causes more warming.

Given its accelerated rate of warming, the Arctic will continue to experience the greatest environmental shifts on the planet. Antarctica is also warming but not as quickly because it is relatively isolated by the *polar vortex* winds and the *Antarctic circumpolar current* that encircle the South Pole.

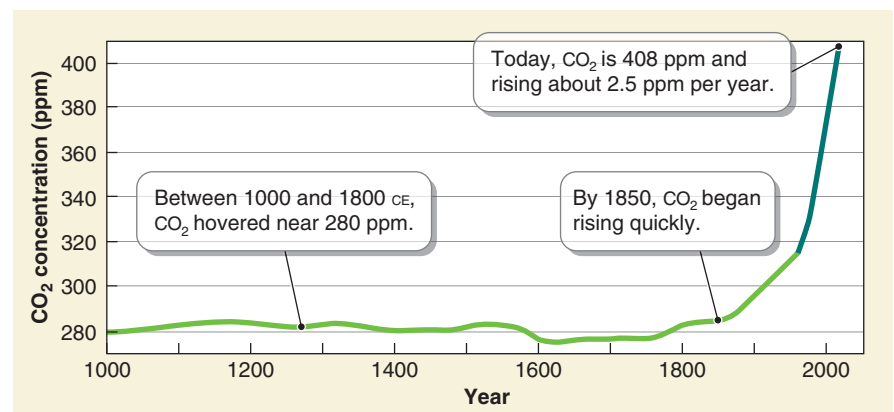
Global Temperature over the Past 800,000 Years

Temperature and CO₂ records from ice cores from Antarctica and Greenland extend back to 800,000 years and have given scientists a firm understanding of atmospheric chemistry and temperature during this time. Earth's average atmospheric temperature is higher now than at any other time in recorded history. But over the course of the past 800,000 years, there have been periods warmer than today. The most recent interglacial warm period was the *Eemian* (also called the *Sangamonian*), which occurred between 130,000 and 115,000 years ago. The average global

Figure 7.16 CO₂ concentrations since 1000 CE. (A) Scientists take ice cores from the Greenland and Antarctic ice sheets in segments. When the segments are placed end to end, the cores are up to 3 km (2 mi) long. Scientists then carefully analyze ancient gas bubbles preserved in the ice. (B) Ancient air from ice cores provides a basis for comparison with the chemistry of today's atmosphere. The light-green graph line shows data from ice cores; the dark-green graph line shows data from direct modern measurements. (Left and center. © Reto Stoeckli; right. British Antarctic Survey/Science Source)



A



B

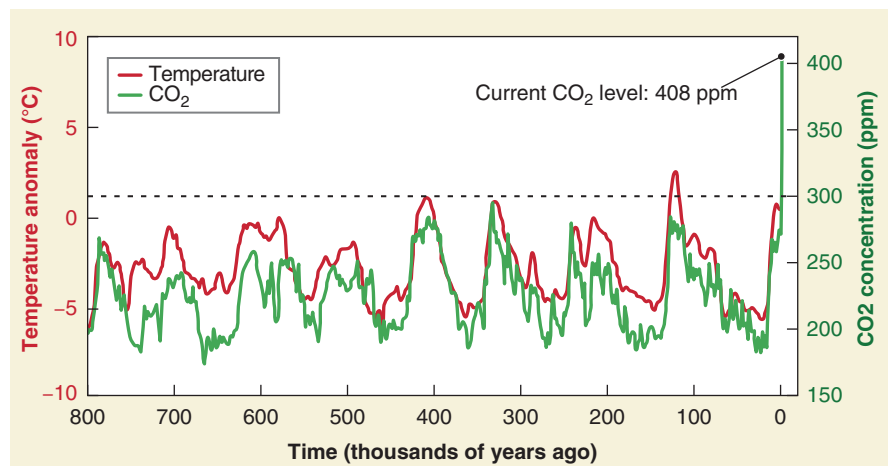
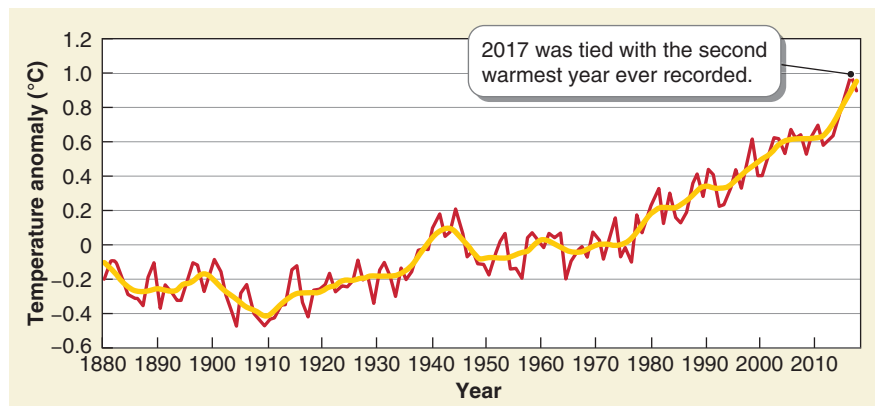
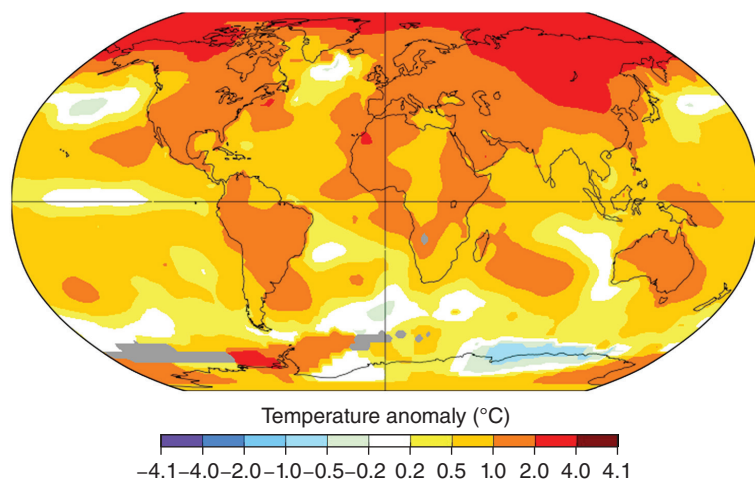


Figure 7.17 Long-term CO₂ and temperature fluctuations. This graph shows atmospheric CO₂ (green line) and temperature (red line), reconstructed from ice cores from Antarctica for the past 800,000 years. Natural CO₂ concentrations never surpassed 300 ppm (shown with the dotted line).

Figure 7.18 Modern temperature record and map. (A) This graph shows recorded global average yearly temperatures from 1880 to 2017. The temperature data are scaled as anomalies above or below the 1951–1980 average, which is defined as 0°C. The orange line shows the long-term average. (B) This world map shows average temperatures for 2017, given as anomalies above or below the 1951–1980 global average, which is defined as 0°C. With a few regional exceptions, everywhere on the map is orange or red, indicating that the world was warmer than average. Note, however, that the Arctic is warming fastest due to the ice–albedo positive feedback. Some Arctic areas were over 4°C (7°F) warmer than the average. (GISTEMP Team, 2018: GISS Surface Temperature Analysis (GISTEMP). NASA Goddard Institute for Space Studies. Dataset accessed 20YY-MM-DD at <https://data.giss.nasa.gov/gistemp/>)



A



B

Video

2017 Takes Second Place for Hottest Year

Available at
www.saplinglearning.com



temperature of the Eemian was perhaps 2°C (3.6°F) above today's average (see Figure 7.17). During that period, the warmth-loving hippopotamus lived as far north as the River Thames in London, and sea level was as much as 9 m (30 ft) higher than it is today due to the melting of ice in Greenland and Antarctica.

Although temperatures during the Eemian were warmer than today's, atmospheric CO₂ concentrations never rose above 300 ppm. Because CO₂ and temperature rise and fall together, it stands to reason that Earth's atmosphere could soon get warmer than it was in

the Eemian because current atmospheric CO₂ concentrations are already far higher and are quickly rising. The **Picture This** feature on page 218 explores Earth's CO₂ and temperature history further.

Is Today's Warming Trend Natural?

Given the evidence, the current warming trend can be explained only by the current increase in atmospheric CO₂ concentrations caused by human activities. There is no known natural phenomenon that can account for this warming trend. The only data set that corresponds to and matches the warming trend since the early 1900s is carbon dioxide (**Figure 7.19**).

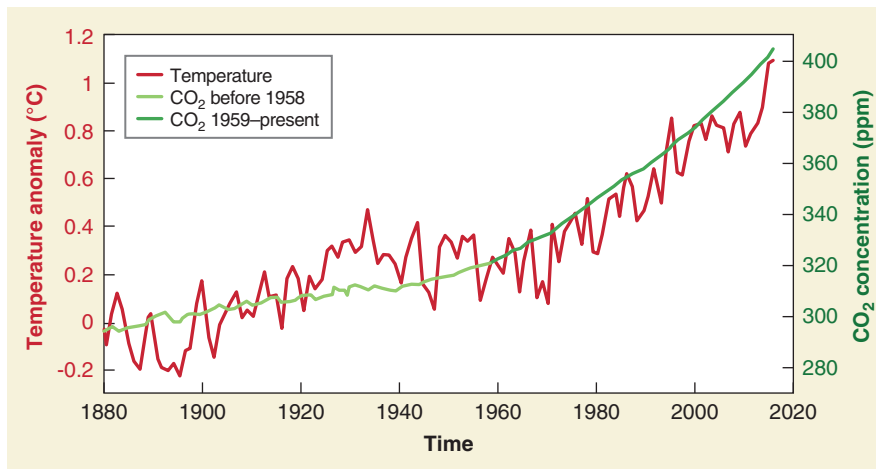
A Strange New World

One question about climate change that often arises is this: "Climate change has happened before, so why should people be concerned now?" Any kind of climate change, whether natural or anthropogenic, can be destabilizing for human societies. There are 7.6 billion people living today, and the population may reach 9 billion by 2050. Earth is vulnerable to small changes in climate for a number of reasons. For example, scientists are concerned that climate change could disrupt agricultural output required to feed the world's population. Other changes could include major demographic, economic, political, and environmental shifts. Human societies have developed during 10,000 years of stable Holocene climate. Any change to the climate system, natural or anthropogenic, will challenge modern societies.

Positive Changes

A warming world could have limited positive aspects for some societies. Canada, for example, is already growing more grapes. It may increase its agricultural output of fruits and vegetables and could even begin growing citrus in the near term. England is at the northernmost limit of wine-grape growing, but that is quickly changing, and many growers there are also switching to grapes in anticipation of a viable and lucrative wine industry.

A new Arctic economy based on shipping, fishing, tourism, and petroleum and natural gas exploration is already opening up. According to the USGS (United States Geological Survey), the Arctic could provide some 30% of the world's natural gas in the coming years. Arctic shipping routes have been blocked by ice year-round until recently, but Arctic ice cover is rapidly diminishing, and these sea routes are now open for part of the year, and more and more cargo is moving through them every year (**Figure 7.20**).



A

Figure 7.19 CO₂ and temperature, 1880 to present. (A) Trends in CO₂ (green line) and temperature (red line) are shown here. Carbon dioxide directly measured (1959 to present) is shown with the dark green line. Earlier values of CO₂ (light green line) are derived from ice cores. The rise in CO₂ closely matches the rise in Earth's temperature. (B) This table lists other factors that cause climate change but do not account for the current warming trend.

POTENTIAL CAUSE OF WARMING TREND	WHY IT DOES NOT EXPLAIN THE CURRENT WARMING TREND
El Niño	El Niño does not last decades.
Solar irradiance changes	The Sun's energy output is not increasing.
Volcanic eruptions	On short time scales, volcanic eruptions cause cooling.
Ocean conveyor belt	The speed of ocean conveyor belt circulation has not increased.
Milankovitch cycles	The warming is far too rapid, and current changes in orbital geometry should be cooling, not warming, the planet.
Mountain uplift and erosion	Uplift and erosion operate on time scales of millions of years.

B

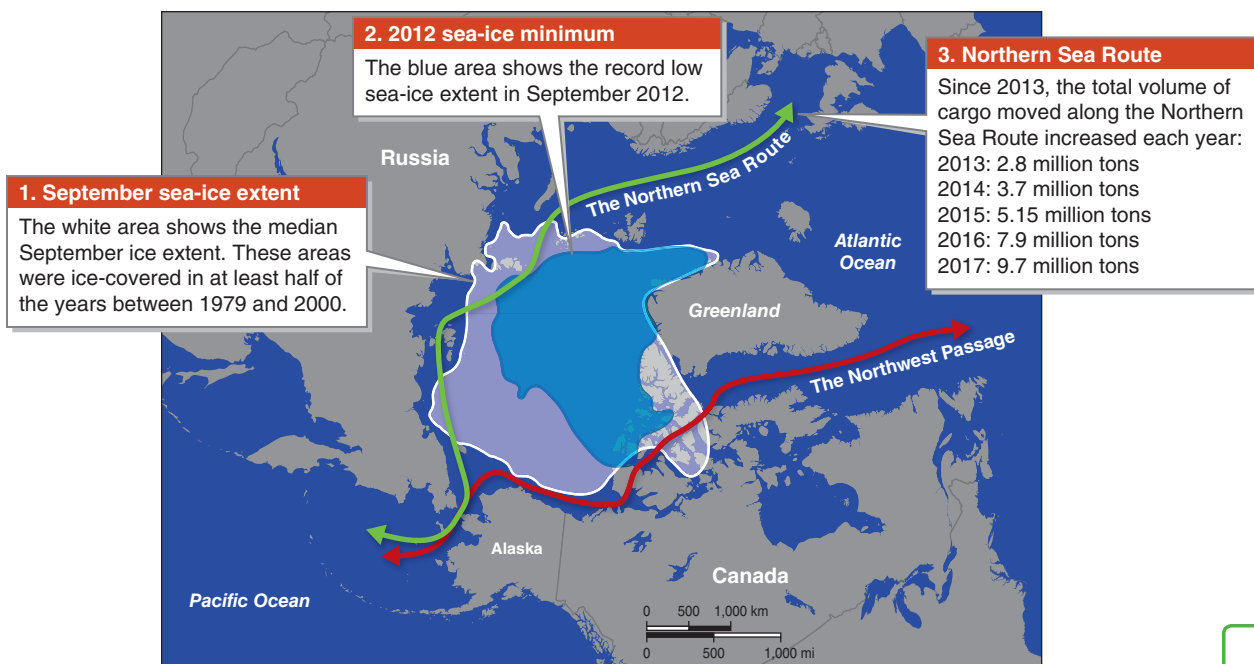


Figure 7.20 Arctic shipping routes. The Northwest Passage and the Northern Sea Route can offer a considerably shorter, faster, and less costly route for shipping traffic between the Atlantic and Pacific oceans. Before 2010, these routes were mostly covered with sea ice in summer. As the Arctic sea ice melts, however, these routes are opening up to shipping traffic. As the routes open up, political friction between northern countries bordering the Arctic Ocean (such as Russia, Norway, Canada, and the United States) is growing.

Video

Arctic Sea Ice Continues a Trend of Shrinking Maximum Extents

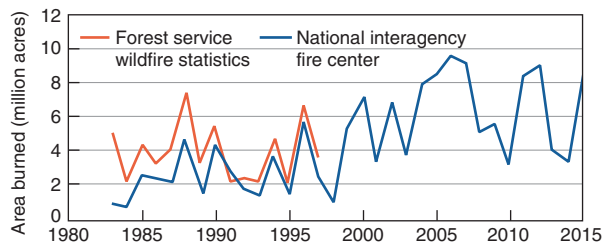
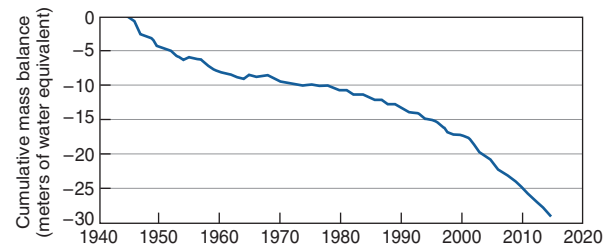
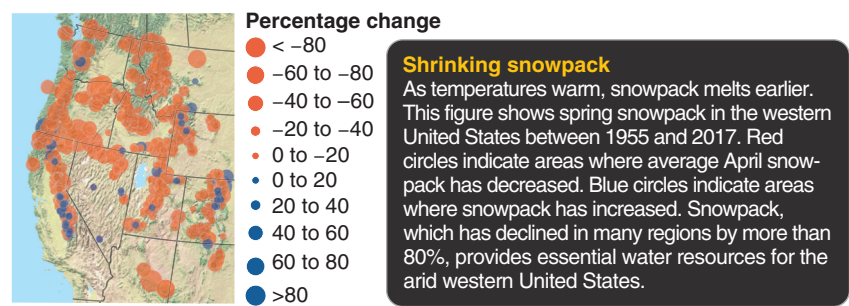
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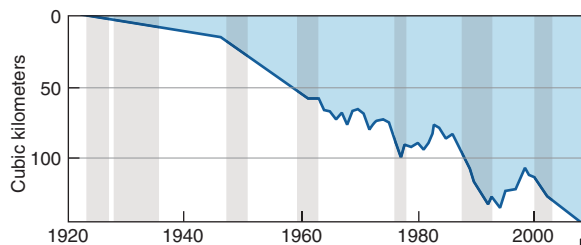
Negative Changes

The benefits of a warmer world are minor compared with the detrimental effects. With each passing year, evidence mounts that rapid shifts in Earth's physical systems are under way. These shifts raise serious concerns for human

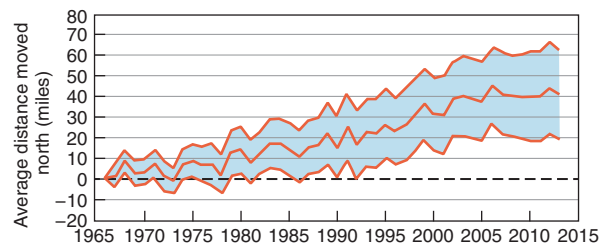
populations in the coming decades. **Figure 7.21** on the following pages presents some of the changes currently happening in Earth's physical systems. In the next 50 years, these changes are certain to continue creating profound challenges for people.



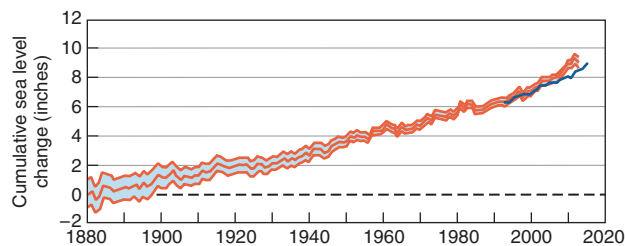
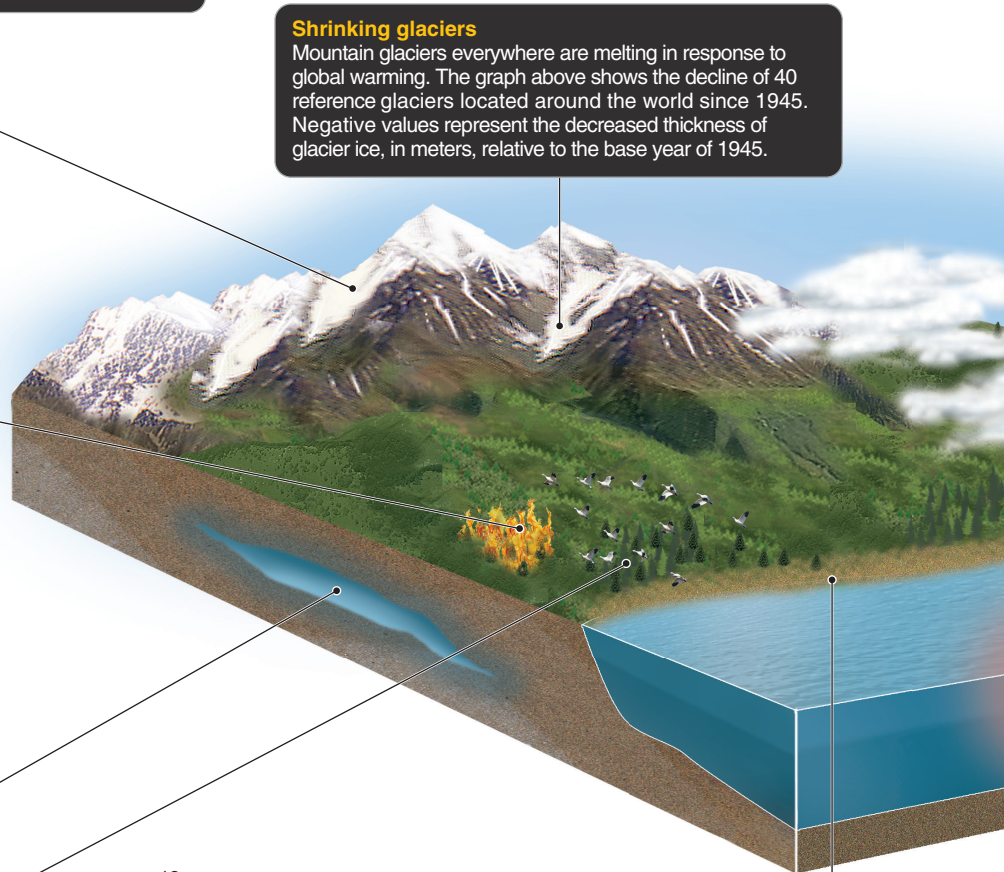
Increasing wildfires
Warmer temperatures and increased evaporation favor increased wildfire activity. This figure shows the area burned by wildfires in the United States between 1983 and 2015. The data in this graph above shows a trend of more area burning each year. Although these data do not show it, wildfires are also becoming more intense.



Groundwater loss
As temperatures rise, the frequency of drought has increased worldwide. Farmers rely on groundwater for their crops in times of drought when surface streams run dry. This graph shows the net trend in declining groundwater in California. During this 93-year period, over 143 cubic km (34 cubic mi) has been lost.

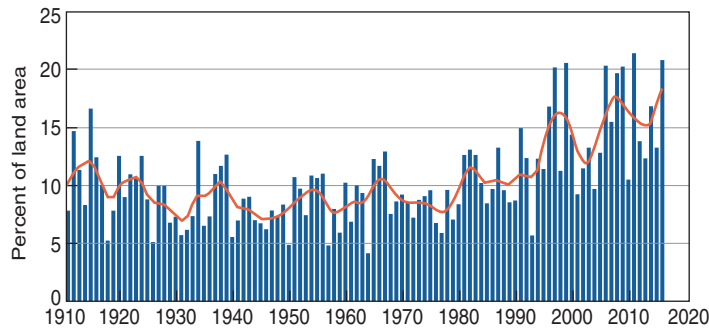


Shifting plant and animal ranges
As the atmosphere warms, plant and animal species are relocating to higher latitudes and elevations. The graph above shows the population movements of 305 bird species in North America from 1966 to 2013. The geographic center of these species shifted north by an average of about 40 mi (64 km). As species relocate, cities, highways, farms, and other human-built landscapes may impede their movement. Also, many species will be unable to relocate fast enough. For this reason, biologists anticipate that many species will become extinct as they attempt to move. The shaded area indicates the range of statistical uncertainty.



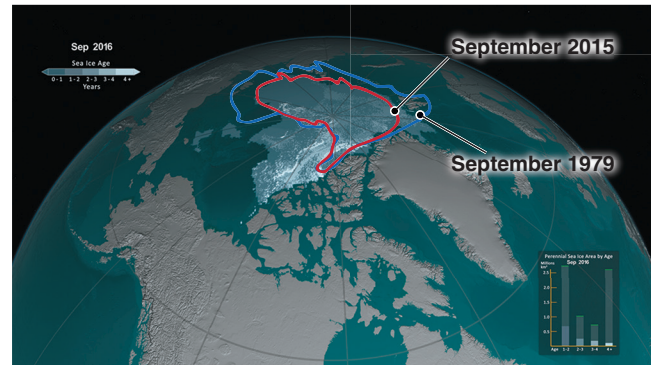
Rising sea level
Global sea level has risen about 23 cm (9 in) since 1880. The rate of sea-level rise is increasing; currently it is about 3.5 mm (0.14 in) per year. Sea-level rise is due to melting glaciers and thermal expansion of seawater as it warms. The shaded area shows the range of statistical uncertainty. Rising sea level threatens coastal populations.

Story Map
The Changing Climate
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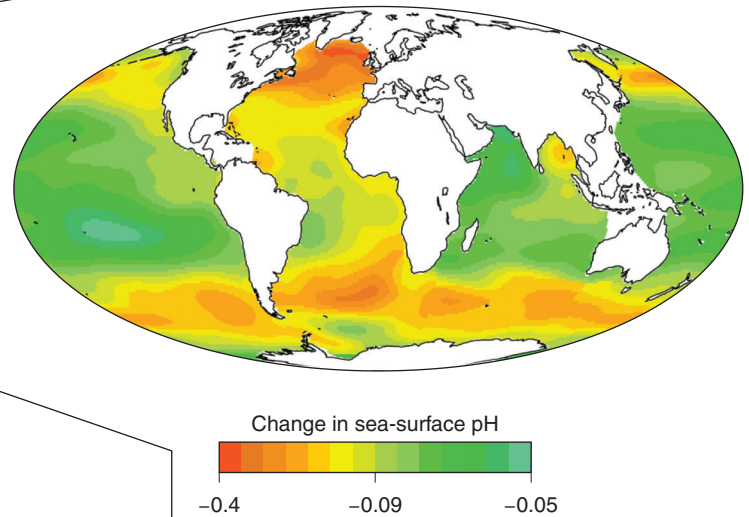
More extreme precipitation

Warmer air increases evaporation rates, leading to more water in the atmosphere and potentially more intense rainfall events. This graph shows the percentage of land area in the lower 48 United States that receives most of its annual precipitation from extreme storms lasting a day or less. The bars are yearly data, and the orange line is a moving average. The land area experiencing extreme rainfall approximately doubled from 1910 to 2015. Extreme climate causes greater loss of property and human lives.



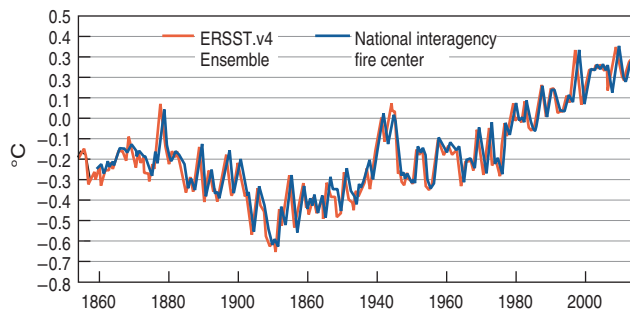
Reduced Arctic sea ice

The Arctic Ocean's ice coverage is lowest each September. The blue line shows the ice minimum in 1979. The red line in the image above shows the ice minimum in 2017. In total, from 1979 to 2017, some 2.4 million km (920,000 mi) of sea ice was lost, an area nearly a quarter the size of the United States. At present rates of loss, the Arctic Ocean will be ice-free in summer by 2040. Loss of sea ice opens shipping routes but threatens Arctic ecosystems.



Increased ocean acidity

The oceans have absorbed about half of all the CO₂ humans have put into the atmosphere since the Industrial Revolution. The CO₂ dissolves in seawater and decreases the water's pH, making the water more acidic and making it harder for shelled organisms to live. The pH of seawater has dropped from about 8.25 to 8.14 since 1850. This rate of pH change in the oceans is the fastest in over 21 million years.



Warming oceans

As the atmosphere warms, so do the oceans. The global ocean has absorbed about 90% of the atmospheric heat energy caused by anthropogenic greenhouse gases. As a result, the oceans' surface temperature has risen 0.56°C (1°F) since 1854. With reduced sea ice at high latitudes, some high-latitude regions have even warmer water, some 5°C (9°F) above normal. The deep ocean is also warming. Warmer oceans threaten coral reefs and force marine species to shift poleward in search of cooler water. Warmer oceans also affect weather, such as by evaporating more water that provides energy to storm systems like hurricanes.

Figure 7.21 Signs of climate change. Shown here are just a few of the extensive physical changes that have been set in motion by global warming. (NOAA)

Picture This An Ice-Free World



(National Geographic Creative)

Atmospheric CO₂ today is roughly 400 ppm; the last time it reached this level was 3 million years ago—well before *Homo sapiens* had evolved. At that time, temperatures were 2°C to 3°C (3.6°F to 5.4°F) higher than today. Global sea level was

up to 25 m (82 ft) higher. Assuming that the present rate of increase continues, by the end of this century, CO₂ will be approaching 1,000 ppm (see the Geographic Perspectives at the end of this chapter). The last time CO₂ was that high was about 55 million years ago, during the *Eocene epoch*. The world was ice-free, and sea level was on the order of 80 m (260 ft) higher than today.

This map illustrates what the current coastline of North America would look like if all the ice in Greenland and Antarctica were to melt. Nearly all the world's coastal cities would be submerged. Most of the Florida peninsula would be under 76 m (250 ft) of water. Cities labeled in blue would be under water. Other white-labeled cities, now far inland, would become coastal cities. It would take 1,000 years or longer for all the ice in Greenland and Antarctica to melt. Scientists know with certainty that sea-level rise of this magnitude will not happen anytime in the near future. Instead, this map illustrates how profoundly climate change can impact Earth's physical geography.

Consider This

1. Why did sea level rise so high during the Pliocene and Eocene? Where did all the water come from?
2. Scientists anticipate that at the end of the twenty-first century, sea level will have risen 1 to 2 m (3.3 to 6.6 ft) higher than today. What strategies and methods might society use to adapt to this change?

Climate Change Projections

The **Intergovernmental Panel on Climate Change (IPCC)** is the world's leading governing body on climate change. The IPCC, established in 1988, is a politically neutral body operating as part of the United Nations. The IPCC's mission is to provide objective, scientific, evidence-based statements about the state of the world's present and future climate, as well as the ramifications of climate change for human societies. In 2013–2014 the IPCC published its *Fifth Assessment Report* (with 16 chapters and more than 2,000 pages), summarizing the peer-reviewed published research of several thousand climate scientists from around the world.

Projecting what the state of the climate will be out to the year 2100 is one of the main goals of the IPCC. This work is accomplished by building general circulation models. A **general circulation model** is a mathematical simulation of the behavior of the atmosphere, oceans, and biosphere that can be used to create long-term climate projections.

General circulation models are developed largely in the same way as the models used in weather forecasting (see Section 6.5).

According to the IPCC's *Fifth Assessment Report*, by the end of this century, the carbon dioxide concentration will likely be somewhere between 550 and 900 ppm, and the global mean surface temperature is likely to have risen between 1.8°C and 4.2°C (3.2°F and 7.6°F) as a result (**Figure 7.22**). **Figure 7.23** shows the geographic areas where temperature and precipitation are most likely to change. The range of uncertainty in the general circulation models results from unpredictable political and economic events. For example, the United States and a few other countries have been resistant to curbing their greenhouse gas emissions. Likewise, while a world leader in clean renewable energy development, China's emissions increased in the past decade due to its strong economic growth, the energy for which has come mostly from coal.

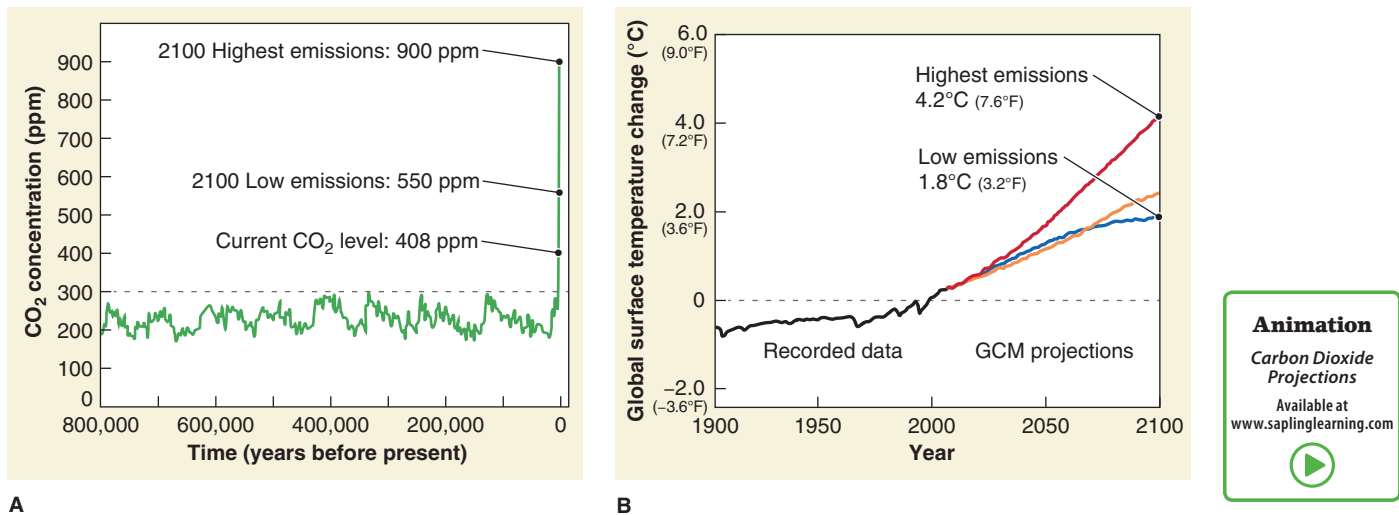


Figure 7.22 Projections of CO₂ concentrations and temperature to 2100.

(A) Projections of atmospheric CO₂ concentrations to 2100 range from 550 ppm to 900 ppm. (B) The three estimates in this graph are based on emissions scenarios created by the IPCC: The “low emissions” scenario (called the RCP4.5 scenario by the IPCC) assumes that greenhouse gas emissions will grow slowly, peak by 2040, and then decline. In the “highest emissions” scenario (called the RCP8.5 scenario), annual anthropogenic greenhouse gas emissions double by 2050 and continue to rise throughout the twenty-first century, just as they did throughout the twentieth century. The orange line represents estimates with moderate emissions.

Animation
Carbon Dioxide Projections

Available at
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Web Map

Projected Temperature Change by 2050
Available at
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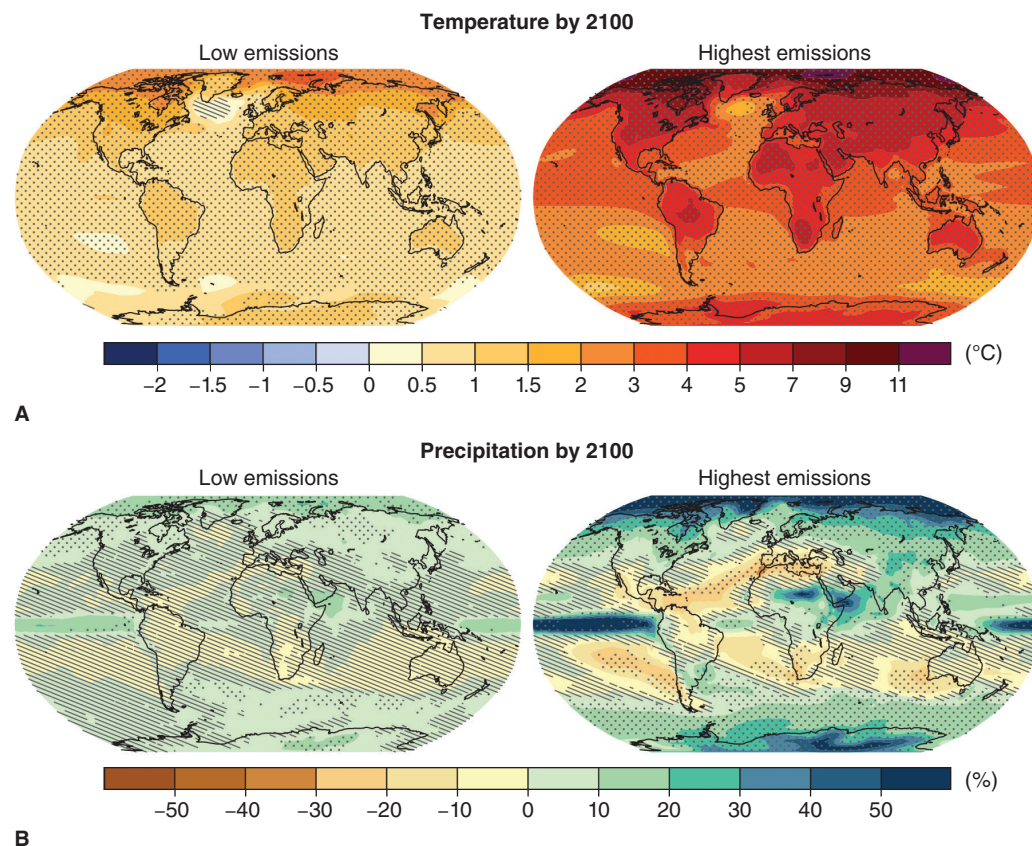


Figure 7.23 Temperature and precipitation change maps for 2100.

(A) The IPCC “low emissions” scenario (left) and “highest emissions” scenario (right) for temperature are mapped. Darker reds indicate higher temperatures. In the “highest emissions” model, temperatures everywhere are far above what they are today. The Arctic shows the greatest change. Stippling or striping indicates areas of high statistical confidence. (B) This map pair shows the IPCC “low emissions” scenario (left) and “highest emissions” scenario (right) for precipitation. Darker green and blue areas are projected to get wetter and tan areas drier. Much of Canada and the northeastern United States are projected to become wetter. The southwestern United States, the Amazon rainforest, and the Mediterranean are expected to become drier. Stippled and striped areas have the highest statistical confidence. (Figure SPM.7 from *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K. and Meyer, L. (eds.)]. IPCC, Geneva, Switzerland.)

Further contributing to the uncertainty of the climate models, feedbacks—such as the permafrost-carbon feedback and the ice-albedo positive feedback—can strongly affect the rate of carbon released to the atmosphere and the severity climate change. Scientists still have an incomplete understanding of how these feedbacks will affect the climate. If the effects of feedbacks are underestimated, the projected temperatures will be too low. If their effects are overestimated, the projected temperatures will be too high.

More than 97% of professional climate scientists agree that human activity is causing climate change. This scientific consensus (not opinion) is based on more than a half century of evidence and more than 50,000 published scientific papers fact-checked by other experts. That people are causing climate change is not in dispute among scientists. Now the problem lies in how to best address the problem, the subject of the next section.

GEOGRAPHIC PERSPECTIVES

7.5 Fixing Climate: The 2-Degree Limit

🕒 **Assess the urgency of addressing climate change and different approaches to tackling the issue.**

In December 2015, 197 countries agreed to the world's most ambitious globally coordinated plan to curb greenhouse emissions. The Paris Agreement (also called COP21, for Conference of the Parties, 21st session) is an agreement within the United Nations Framework Convention on Climate Change (UNFCCC). Its primary aim is to limit the warming of the atmosphere by 2100 to 2°C (3.2°F) above the pre-industrial era temperature. Only Syria and Nicaragua did not sign on to the agreement. (Syria is torn by civil war, and Nicaragua protested that the agreement was not ambitious enough.) Scientists think that anything above 2°C will trigger positive feedbacks, such as the permafrost-carbon feedback, and uncontrolled warming. Many scientists think that even 2°C is dangerously warm and that the aim should be to keep the warming under 1.5°C above pre-industrial levels. A secondary goal of the Paris Agreement, therefore, is to keep

the warming limited to 1.5°C (2.7°F). **Figure 7.24** provides more details about the Paris Agreement.

The Carbon Budget

To make the 2-degree goal, the world must act very quickly. Because the atmosphere has already warmed 0.99°C (1.78°F) since pre-industrial times, we're already halfway to the 2-degree limit. The international scientific community, speaking through the IPCC, states that the total carbon emissions budget to meet the Paris Agreement goal is 1 trillion tons, or 1,000 PgC. (PgC = petagrams of carbon; 1 petagram [Pg] = 1 billion tons). Since the Industrial Revolution, humans have emitted roughly 550 PgC of carbon, causing 1°C of warming. That leaves 450 PgC left in the carbon emissions budget before we exceed the 1,000 PgC, 2-degree limit.

From 2001 to 2015, global carbon emissions rose from 7.8 PgC per year to 9.8 PgC per year. Currently, annual emissions of carbon are about 10 PgC. Assuming that this rate were to hold constant, in 45 years we would reach the limit of a cumulative total of 1,000 PgC emissions. Thereafter, in order to stay under 2°C warming, the amount of carbon entering the atmosphere would have to equal the amount naturally leaving the atmosphere through carbon sinks, a situation called *carbon neutral*. *Carbon sinks* are processes or environments that pull carbon out of the atmosphere; the oceans, weathering, and photosynthesis, for example, are carbon sinks.

The Paris climate agreement: key points

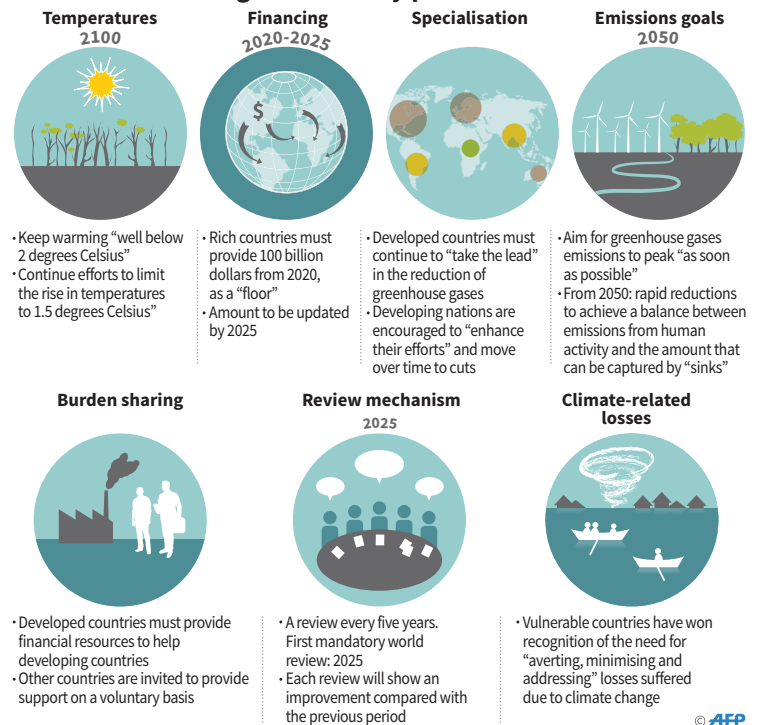


Figure 7.24 Paris Agreement key points. This graphic summarizes the major elements of the Paris Agreement. The historic agreement will go into effect in 2020. (© AFP)

Keep in mind that these numbers are not written in stone. For example, if the annual rate of emissions slowly decreases, then the time it takes to reach the 1,000 PgC limit will be longer; if the rate of emissions increases, then there is less time. Changes in the rate of global deforestation could also change the timetable. In addition, acceleration of positive feedbacks, such as the permafrost-carbon feedback and the wildfire-carbon feedback, could greatly reduce the time it takes to reach 2°C of warming.

Only the “low emissions” IPCC scenario will keep us under 2°C of warming (see Figure 7.22). Under this scenario, CO₂ emissions must slow and peak by 2040 and then decline by about 66% by the year 2100. All this must be done while the world population grows and economic development leads to greater demand for electricity (which is now mostly generated from coal) and cars (which now run mostly on petroleum) in developing countries with large populations, such as India and China.

In response to this challenge, the world is rapidly building a **green economy**—a sustainable economic system that has a small environmental impact and is based on carbon-free energy sources. For example, according to the U.S. Department of Energy, in 2016 solar energy producers employed twice as many workers as all the traditional fossil-fuel sectors combined. Electricity from the wind and from sunlight are two central pillars of the burgeoning green economy (see Sections 3.6 and 5.5). There will always be a use for fossil fuels (or *hydrocarbons*) in society, such as for machinery lubricants and manufacturing materials such as plastics. But electricity generated from fossil fuels, such as by burning coal, will have to be all but phased out by 2100 if we are to resolve our climate problem.

Unburned fossil fuels in the ground represent more than 2,800 PgC, an amount worth over \$20 trillion. If the world is to avoid major climate change, these reserves of fossil fuels must remain in the ground. In other words, the fossil-fuel industries that own these reserves must forsake \$20 trillion in revenue. At the same time, the up-and-coming green economy is becoming hugely profitable. This clash is at the heart of why the climate change issue has become so politically charged.

Curbing Carbon Emissions

How, specifically, do we limit carbon emissions? **Table 7.4** provides eight large-scale ways to reduce carbon emissions. Each of the rows in the table is an action that could reduce global carbon emissions by 1 PgC annually if it were fully implemented by 2050. Many other ways to reduce carbon are not shown on this table.

The large-scale carbon-reduction efforts like those in Table 7.4 simply won’t happen unless they are legislated by government at the municipal, state, and national levels. Their implementation requires *top-down* regulations (as opposed to *bottom-up*, or *grassroots*, campaigns). Carbon taxes and cap-and-trade programs are other regulatory tools available to reduce carbon emissions.

Carbon Taxes

Carbon taxes are taxes levied on CO₂ emissions that exceed a predetermined level. They can be applied to a single factory, a city, or even a whole state or province. Much like water meters on houses reduce household water use, these taxes provide a strong incentive to reduce carbon emissions by switching to carbon-free energy. Carbon tax revenue can

Table 7.4 Carbon-Reduction Actions

ACTION	HOW TO DO IT
Cars: Double the fuel efficiency of all cars worldwide from 30 to 60 mpg.	Improve technology in vehicles. Phase out inefficient vehicles.
Cars: Halve the number of miles traveled by cars each year.	Increase telecommuting and improve city design and public transit.
Buildings: Reduce energy use in all buildings by 25%.	Improve insulation and building design. Improve efficiency of heating and cooling, lighting, and appliances.
Coal efficiency: Improve coal power plant efficiency from the current 40% to 60%.	Improve technology for burning coal and converting it to electricity.
Carbon capture and storage (CCS): Capture CO ₂ emissions before they enter the atmosphere.	Retrofit (update) 800 large coal power plants with CCS technology.
Solar energy: Increase photovoltaic solar power capacity.	Increase today’s photovoltaic capacity by 700 times. This would require 2 million hectares of land (see Section 3.6).
Wind energy: Increase wind power capacity.	Increase today’s wind capacity by a factor of about 40. This would require 30 million hectares (74 million acres) of land (see Section 5.5).
Deforestation: Reverse deforestation in the tropics.	Provide economic alternatives to cutting forests for developing countries. Reduce demand for forest products in developed countries by supporting recycling and more efficient manufacturing.

be channeled into further developing carbon-free energy and other sectors of the green economy. Some 20 countries—including the United Kingdom, Sweden, India, Australia, and New Zealand—currently have carbon taxes. Some Canadian provinces, such as Quebec, have implemented carbon taxes. In the United States, carbon taxes are politically unpopular.

Cap-and-Trade

In a *cap-and-trade* system, a government allocates carbon “credits” to carbon producers, such as manufacturing companies. Fines result when emissions exceed the quota established for the credits. A polluting company may purchase more carbon credits from other cleaner companies that have extra carbon credits to sell. The limit on the overall number of carbon credits reduces the total carbon emissions of a country. All industrialized countries have some form of cap-and-trade system in place.

What Can You Do?

The challenge of coping with climate change can seem overwhelming to an individual. For many of us, almost all of our daily activities rely on energy from fossil fuels and emit CO₂ into the atmosphere. The average car emits about 5.5 metric tons of CO₂ each year. Heating, cooling, and electricity use in the average house in the United States produce about 11 metric tons of CO₂ each year. Only rare individuals are going to volunteer to go without driving, heating their homes, and using electricity, which have become necessities of modern life. In the green economy, all these activities will become *decarbonized*, meaning they will not result in CO₂ emissions.

Renewable and carbon-free energies, like wind and solar, will form the foundation of our energy needs.

Understanding your own personal carbon footprint provides useful insight. A **carbon footprint** is the amount of greenhouse gases (particularly CO₂) that an activity generates. Many of the steps required to reduce your personal carbon footprint call for lifestyle changes but not necessarily sacrifices (**Table 7.5**). There are many online “carbon calculators” that allow you to estimate your CO₂ emissions and consider ways to reduce your carbon footprint.

Geoengineering

Because of the long atmospheric lifetime of CO₂, any increase in it is considered permanent as far as human societies are concerned. If the world were to magically stop emitting all carbon today, CO₂ concentrations would plateau immediately, but it would take much more than 10,000 years for natural carbon sinks to absorb the CO₂ out of the atmosphere and return atmospheric CO₂ to pre-industrial levels. If the world exceeds the 1,000 PgC limit, we may have to resort to geoengineering solutions. A growing number of scientists are convinced that geoengineering solutions are already unavoidable. Geoengineering (or *climate engineering*) is the deliberate, global-scale modification of Earth’s environments to improve living conditions for people. There are two approaches to engineering the climate: *carbon dioxide removal* and *solar radiation management*. With the exception of planting real trees, each of these geoengineering schemes involves immense costs, serious environmental risks, and unpredictable effects on climate.

Table 7.5 Carbon Footprint Reduction	
ACTIVITY	REDUCING YOUR CARBON FOOTPRINT
Reduce, reuse, recycle	Generating less waste and recycling reduce the amount of greenhouse gases emitted by resource extraction, manufacturing, transport, and disposal of materials.
Driving	Living closer to work, biking, walking, using public transportation, carpooling, and combining errands for fewer trips reduce the amount of fuel burned.
Home energy use	Insulating the attic and outside walls and installing LED lighting and efficient appliances reduce energy use.
Water use	Purifying and distributing water require energy. Using less water consumes less energy.
Renewable energy use	Using solar and wind energy decreases reliance on fossil fuels. Many local power companies allow users to select whether their power comes from conventional or renewable sources.
Diet	Raising livestock for meat is more carbon-intensive than growing plants for direct human consumption. Eating organic food reduces the use of fossil-fuel fertilizers. Eating locally produced food reduces the need to transport food long distances.
Flying	Flying is a carbon-intensive activity. Flying less reduces fuel use.
Political engagement	Climate-friendly legislation can be an effective way to manage greenhouse gas emissions. Vote for the climate!
Carbon offsets	Carbon offsets are investments in renewable, carbon-free energy sources such as wind energy and solar energy. These projects can reduce carbon emissions from conventional energy sources such as coal and oil by helping phase those out and replacing them with more projects on carbon-free energies.

Carbon Dioxide Removal

Techniques used to remove CO_2 from the atmosphere range from *forestation* (planting trees), to fertilizing the oceans with nutrients, to capturing CO_2 directly from the air by using “artificial trees” (**Figure 7.25**). Some of the techniques, such as planting trees, have no risks. On the other hand, some techniques are inherently—and unpredictably—risky. For example, fertilizing the microscopic photosynthetic phytoplankton in the oceans with iron would stimulate their growth and pull CO_2 from the atmosphere and put it into the oceans—but no one knows what the effects would be on marine ecosystems. Similarly, it would take billions of “artificial trees” absorbing CO_2 to have a measurable effect. The cost of such a system would be astronomical, and it would take decades or longer to build such a system. Another method, carbon capture and storage (CCS), involves removing carbon emissions from coal-burning power plants before they enter the atmosphere. One major hurdle to these methods is that there is no known way to dispose of or use the immense amounts of captured and liquefied or powder-form CO_2 that would result from these methods. Scientists are working to economically convert captured waste CO_2 into useful products, like fuels, building materials, and plastics.

Solar Radiation Management

All solar radiation management techniques either propose to increase Earth’s albedo or decrease the

intensity of sunlight striking Earth from out in space. Earth’s albedo could in theory be increased by injecting aerosols into the stratosphere with airplanes, mimicking the cooling effects of very large volcanic eruptions (see Section 7.2). Similarly, cloud seeding (see Section 4.7) could be used to make more reflective and cooling clouds. A more ambitious suggestion is to place a cloud of millions of small objects such as mirrors in an orbitally stable point between Earth and the Sun (called a *Lagrange point*). Such a solution would cool Earth by absorbing or reflecting sunlight for about 50 years. The costs and political details of such projects would be major hurdles to these schemes. Also, no one knows how the climate system would respond to such efforts.

The science is clear on one important point: The least expensive and least destructive path forward is to curb our greenhouse gas emissions. Engineering Earth’s climate in response to increasing droughts, floods, disease, sea-level rise, and shifting agricultural zones would be far more costly and dangerous to society than curbing greenhouse gas emissions right now. Since the year 1976, every decade has been warmer than the previous one (see Figure 7.18). Atmospheric CO_2 concentrations and temperatures are still rising fast. But at the same time, green economies are quickly gaining momentum. It remains to be seen how this unintended planetary-scale experiment will play out.

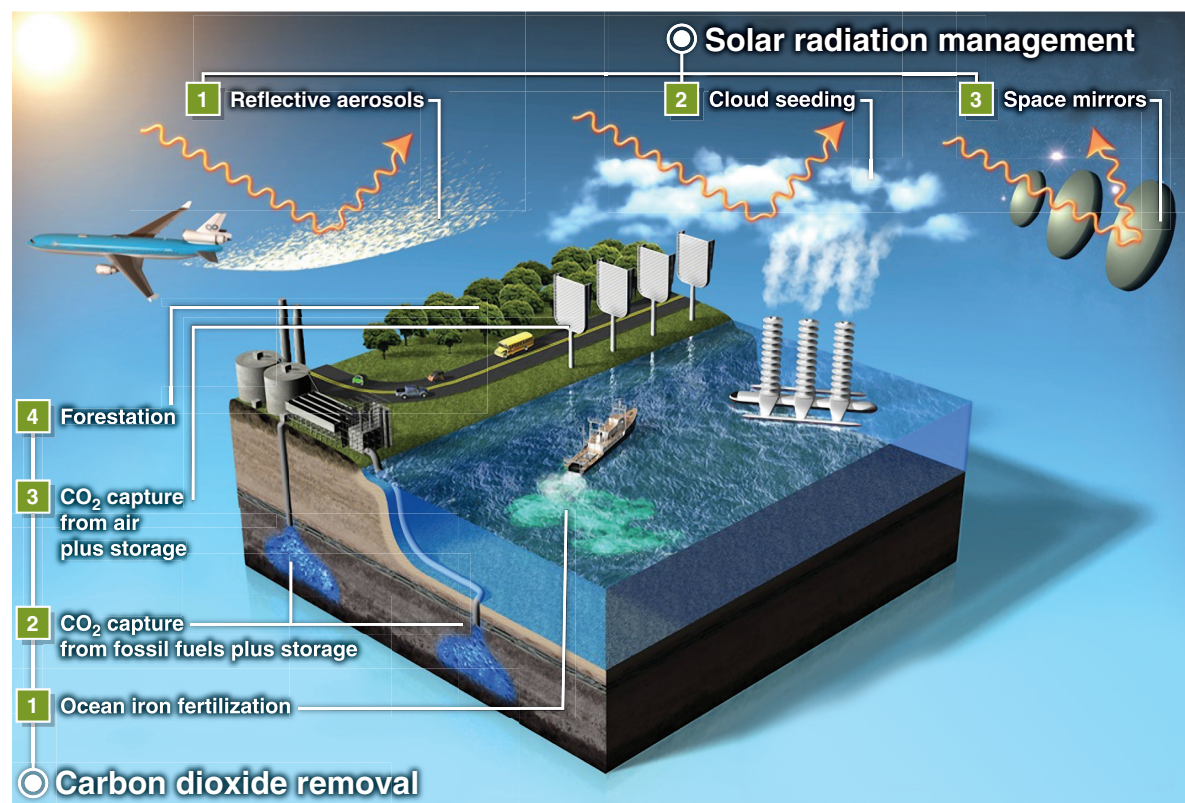


Figure 7.25
Geoengineering methods. The various geoengineering methods available today are illustrated here. All involve huge expense, and most involve considerable risk of uncontrolled changes to the climate system. (Remik Ziemlinski/Climate Central)

Chapter 7 Study Guide

Focus Points

The Human Sphere: Nuisance Flooding: Nuisance flooding events are increasing due to rising sea level.

7.1 The Climate System

- **Weather and climate:** Climate is the long-term average of the daily weather and the frequency of extreme events such as hurricanes, heat waves, or flooding rains.
- **The climate system:** The climate system is composed of the atmosphere, biosphere, lithosphere, hydrosphere, and cryosphere.
- **Temperature increase:** The average global atmospheric temperature has risen by 0.99°C (1.78°F) since 1880. Most of this warming is due to human activities.
- **Climate change:** Climate change occurs when the long-term trend of meteorological variables or weather extremes, such as the average temperature or the number of heat waves, changes.
- **Climate forcings and feedbacks:** Climate forcings, such as volcanic eruptions, are not influenced by the climate system; climate feedbacks, such as the permafrost–carbon feedback, change climate from within the climate system and are strongly influenced by climate.

7.2 Climate Trends, Cycles, and Anomalies

- **Modes of climate change:** Climate change occurs through long-term trends (Cenozoic cooling), repeating cycles (Milankovitch cycles), and unpredictable anomalies (volcanic eruptions).
- **The Holocene:** The Holocene (spanning the past 11,700 years) is Earth's current warm interglacial period. Climate has been unusually stable during the Holocene.
- **Rapid climate change:** Climate can rapidly switch between different states on a time scale of decades.
- **Reconstructing past climates:** Elements of Earth's past climates are recorded in various natural materials, including tree rings, glaciers, cave deposits, and ocean sediments.

7.3 Carbon and Climate

- **Carbon cycles:** Carbon is removed from the atmosphere, oceans, and biosphere and stored for many millions of years in the lithosphere in the long-term carbon cycle. Carbon moves relatively quickly among the atmosphere, biosphere, and oceans in the short-term carbon cycle.
- **Human activity and carbon cycling:** Each year, burning of fossil fuels and deforestation move up to 40 billion metric tons of carbon from the lithosphere and biosphere into the atmosphere.

7.4 Climate at the Crossroads

- **Carbon dioxide and temperature:** Atmospheric CO₂ concentrations and temperatures have risen and fallen together during the past 800,000 years.

- **Anthropogenic greenhouse effect:** Natural atmospheric CO₂ concentrations have not exceeded 300 ppm over the past 800,000 years. Because of human activities, atmospheric CO₂ concentrations are now 400 ppm and rising 2.5 ppm per year. As a result, atmospheric temperatures are rising.
- **Arctic amplification:** The ice–albedo positive feedback is warming the Arctic more than twice as quickly as the rest of the world.
- **Causes of the current warming trend:** No known natural climate forcing factor, such as volcanic activity or sunspot activity, can explain the current warming trend.
- **Effects of warming:** The negative aspects of warming far outweigh any positive aspects. Among the unwanted effects of climate change are sea-level rise, warmer and more acidic oceans, increased wildfires, and shifting agricultural zones.
- **Climate projections:** Projections based on computer modeling indicate that the mean global temperature will be between 1.8°C and 4.2°C (3.2°F and 7.6°F) warmer by 2100.

7.5 Geographic Perspectives: Fixing Climate: The 2-Degree Limit

- **2-degree goal:** Most climate scientists conclude that limiting atmospheric warming to less than 2°C (3.2°F) could prevent further dangerous climate change. To meet this goal, cumulative global carbon emissions must not exceed 1,000 PgC.
- **Cutting carbon:** There are many ways to cut carbon emissions, ranging from increasing wind and solar energies, to taxing carbon, to living closer to work.
- **Geoengineering:** Various geoengineering schemes are available to remove carbon from the atmosphere, such as building artificial “trees” and blocking sunlight with stratospheric aerosols. With the exception of simply planting more trees, each of them involves high expense and risk.

Key Terms

Arctic amplification, 213
carbon cycle, 208
carbon footprint, 222
Cenozoic era, 202
climate, 199
climate forcing factor, 200
general circulation model, 218
glacial period, 203
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weather, 199
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Concept Review

The Human Sphere: Nuisance Flooding

1. What is nuisance flooding, and why is it occurring more commonly today than in the past? Where does it occur?

7.1 The Climate System

2. What is the difference between weather and climate?
3. How is *climate* defined?
4. Compare the definitions of *weather* and *climate*. Is one day of record heat an example of weather or climate? What about one warmer-than-average year? A decade of warmer-than-average years?

5. In addition to the atmosphere, what are the other parts of the climate system?
6. What happened to temperatures in the Northern Hemisphere during the Younger Dryas?
7. By how much has the average temperature of the lower atmosphere increased over the past 100 years?
8. Is the temperature increase over the past 100 years an example of weather or climate change? Explain.
9. If a severe storm strikes, can scientists definitely say it was caused by climate change? Explain.
10. What are climate forcing factors? How are they different from climate feedbacks? List examples of each.
11. Explain how ice cover at high latitudes can function as a positive feedback that destabilizes climate or as a negative feedback that stabilizes climate.

7.2 Climate Trends, Cycles, and Anomalies

12. What caused the Cenozoic cooling trend?
13. Describe the Quaternary ice age in terms of its timing and repeated climate cycles. Describe the climate of the Holocene Epoch.
14. What are Milankovitch cycles? With what kind of climate change pattern are they associated?
15. What are glacials and interglacials? About how long, on average, has each lasted during the past million years? What caused them: climate forcing or climate feedbacks?
16. Provide an example of a climate anomaly. Do climate forcings or climate feedbacks cause anomalies?
17. When did the Medieval Warm Period and Little Ice Age happen? What caused them? How did they affect human society?
18. What natural archives do paleoclimatologists examine to reconstruct ancient climates and environments?

7.3 Carbon and Climate

19. Where is most carbon on Earth stored? How does carbon enter and leave this long-term storage?
20. Compare and contrast the long-term carbon cycle with the short-term carbon cycle. Explain how carbon moves within each of these cycles.
21. What two main types of human activity are transferring carbon to the atmosphere? How many billions of metric tons of carbon are transferred to the atmosphere each year?

7.4 Climate at the Crossroads

22. What is the current rate of increase of CO₂ concentration in the atmosphere each year, in parts per million?
23. What is the Keeling curve? What does it show?
24. How do we know what prehistoric CO₂ concentrations were? Compare current CO₂ concentrations in the atmosphere with those over the past 800,000 years.
25. What concentration (in ppm) did natural atmospheric CO₂ not exceed over the past 800,000 years?

26. What is the current atmospheric CO₂ concentration (in ppm)? Where is this “extra” carbon coming from?
27. Describe the relationship between CO₂ and global atmospheric temperature.
28. Geographically, where is most of the current warming trend happening? Why is it happening there?
29. Are there any natural climate forcing factors that can explain the current warming trend?
30. What are some of the responses of Earth’s physical systems to the current warming trend? What changes in Earth’s physical systems are happening right now?
31. What is the IPCC? What range of atmospheric CO₂ and temperatures does the IPCC project for 2100?
32. What is a general circulation model? Why do general circulation models make a range of climate projections instead of just a single climate projection?

7.5 Geographic Perspectives: Fixing Climate: The 2-Degree Limit

33. Why does the IPCC state that the goal should be to limit warming to 2°C? What are scientists concerned about happening if the warming exceeds 2°C?
34. How many PgC can humans emit to the atmosphere in total and still remain under 2°C of warming?
35. How many PgC has human society thus far emitted in total? How much warming has that caused?
36. How, specifically, can society reduce its carbon emissions?
37. What are carbon taxes, and how do they work? What is cap-and-trade, and how does it work?
38. How, specifically, can individuals reduce their carbon emissions?
39. What is geoengineering? List and describe examples of geoengineering that may be used to change Earth’s climate.

Critical-Thinking Questions

1. What differences and what similarities can you think of between the Greenland Norse and modern societies in the context of vulnerability to climate change?
2. Has reading this chapter altered your view on climate change? Explain.
3. Some scientists think we should begin ramping up geoengineering projects immediately. Do you agree or disagree with this view? Support your answer.
4. Why has the topic of climate change been politically controversial? What views might people with different backgrounds and interests take on this topic?
5. Read through Table 7.5 again. Do you find these individual approaches to addressing climate change agreeable or disagreeable? Specifically, do you think altering one’s diet or plane travel is a reasonable response to the problem? Explain.

Test Yourself

Take this quiz to test your chapter knowledge.

1. **True or false?** A single year of record-breaking heat is a definite sign of climate change.

2. **True or false?** In just four days, human activity emits the same amount of CO₂ as natural emissions do over a whole year.
3. **True or false?** Most of Earth’s carbon is stored in the lithosphere.
4. **True or false?** To safely stabilize climate, human carbon emissions must not exceed 2,000 PgC in total.

5. **True or false?** The ocean conveyor belt system caused the Cenozoic cooling trend.
6. **Multiple choice:** During the past 800,000 years, natural atmospheric CO₂ concentrations did not rise above
 - a. 100 ppm.
 - b. 200 ppm.
 - c. 300 ppm.
 - d. 400 ppm.
7. **Multiple choice:** Today's atmospheric CO₂ concentration is about
 - a. 200 ppm.
 - b. 300 ppm.
 - c. 400 ppm.
 - d. 500 ppm.
8. **Multiple choice:** Why are the oceans becoming more acidic?
 - a. because they are warming
 - b. because of ocean currents
 - c. because organic activity is causing acidification
 - d. because they are absorbing CO₂ from the atmosphere
9. **Fill in the blank:** The _____ is a graph of measurements that show increasing CO₂ concentrations in the atmosphere.
10. **Fill in the blank:** The study of ancient climate is called _____.

Online Geographic Analysis

Tornado Analysis

In this exercise we analyze tornado activity in the United States.

Activity

Go to <https://www.ncdc.noaa.gov/sotc/>. This is a National Oceanic and Atmospheric Administration (NOAA) web page. This "State of the Climate" page provides global climate data. Using the default settings on the page, click the "Submit" button.

Picture This. Your Turn

Annual Carbon Dioxide Increase

The graph shows atmospheric concentrations of CO₂ measured at the Mauna Loa Observatory. The green line shows seasonal variation around the annual average (black line). Apply what you have learned in this chapter to answer the following questions.

1. Why does the global atmospheric CO₂ concentration fluctuate seasonally?
2. How has human activity changed the long-term carbon cycle to cause the rising trend shown in this graph?

1. **Scroll down and click and pull up the world map that shows extreme climate events worldwide. Compare extreme high temperature events to extreme low temperature events. Which do you see more of?**

2. **Where did the most extreme temperature event occur?**

Close the map and scroll back up to the selection fields. In the "Year" field select "2017." In the "Month" field select "annual." Click the "Submit" button.

3. **Scroll down to the table that lists the rankings of the warmest years. What 3 years were top ranked?**

4. **Only 1 year was not in the twenty-first century. Which year was it?**

Scroll back up to the selection field. In the "Report" field select "Global Snow and Ice." Keep the other fields the same. Click the "Submit" button.

5. **Scroll down to "Sea Ice Extent." Click the graph to enlarge it if you need to. What year experienced the smallest sea-ice extent?**

6. **On what date in 2016 did Arctic sea ice reach its smallest extent? Compared to the entire record, what was 2016 ranked in smallest minimum sea ice?**

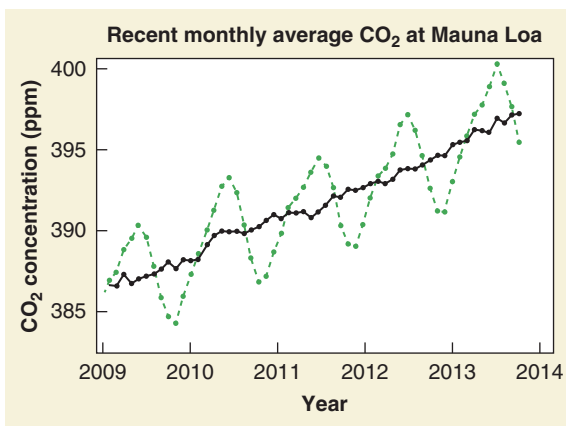
Now go to <https://data.giss.nasa.gov/gistemp/maps/>. This NASA "GISS Surface Temperature Analysis" web page maps global temperatures. In the "Mean Period" field select "Annual (Dec-Nov)." In the "Time Interval" boxes select "2016" for both the "Begin" and "End" fields. Click the "Make Map" button.

7. **Scroll down to the surface winter temperature map. Where is the greatest warming taking place?**

8. **Why did that area experience the most warming?**

9. **Up to how much warming did that area experience, in both Celsius and Fahrenheit?**

10. **The data are given as "anomalies" in relationship to what?**



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