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Smokestacks spew human-caused emissions into the atmosphere.
Emissions from the combustion of fossil fuels by power plants, cars, and factories are released into the atmosphere. These human-caused emissions are affecting all parts of the environment and especially the oceans.

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"Human-induced climate change is a reality, not only in remote polar regions and in small tropical islands, but everyplace around the country, in our own backyards. It's happening. It's happening now. It's not just a problem for the future. We are beginning to see its impacts in our daily lives. More than that, humans are responsible for the changes that we are seeing, and our actions now will determine the extent of future change and the severity of the impacts."

—Jane Lubchenco,
marine ecologist and NOAA Chief Administrator (2009)

16 THE OCEANS AND CLIMATE CHANGE

CHAPTER AT A GLANCE

- Humans are adding vast amounts of greenhouse gases to the atmosphere, which is causing Earth's climate to change.
- As a result of climate change, there will be many unintended and severe changes in the ocean, including ocean warming, more intense hurricanes, increasing ocean acidity, changes in deep-water circulation, melting of polar ice, and rising sea level.
- Action must be taken to reduce human-caused greenhouse gases.

Climate change and global warming are topics that have received much media attention recently. These topics are often in public opinion polls and in newspaper headlines; as such, they have spurred intense debate on whether climate change is natural or human caused and what climate changes are likely to occur in the future. These topics have also become the subject of numerous international conferences and of complicated discussions among scientists. The urgent challenge of human-induced climate disruption continues to be one of the most studied aspects of climate change.

From a broad perspective, the geologic record has shown that Earth's climate is variable. Evidence from fossils in sea floor sediments and rocks on land suggest that practically everyplace on Earth has experienced dramatic swings in climate over geologic time. Some examples of this are stable continental regions that have remained at high latitudes yet display low-latitude fossils and coal deposits, sea floor sediments that represent much warmer or colder conditions than at present, and ice age deposits on the sea floor.

Recent research on human activities and their impact on the environment has demonstrated that people are inadvertently changing Earth's climate. Unlike changes in the past, modern climate change is dominated by human influences so large that they exceed the bounds of natural variability. Moreover, these changes are likely to continue for thousands of years. Climate changes can be very disruptive not only to humans but to many other life forms as well, especially if they occur as rapidly as some scientists predict.

In this chapter, we will examine Earth's climate system, the science that indicates Earth's recent and dramatic climate change, how the greenhouse effect works, how the oceans are being affected, and what can be done about this problem.

16.1 What Comprises Earth's Climate System?

Climate is defined as the conditions of Earth's atmosphere—including temperature, precipitation, and wind—that characteristically prevail in a particular region over extended time spans.

Obtaining a full understanding of Earth's climate involves studying more than just the atmosphere. Earth's climate is a complex and interacting system that includes the atmosphere, hydrosphere, geosphere, biosphere, and cryosphere.[1] Earth's **climate system** involves the exchanges of energy and moisture that occur among the five spheres. These exchanges link the atmosphere to the other spheres so that the entire system functions as an interactive unit. Changes to the climate system do not occur in isolation. Rather, when one part of it changes, the other components also react.

[1]The cryosphere (*kruos* = icy cold, *sphere* = a globe) refers to the ice and snow that exists at Earth's surface.

STUDENTS SOMETIMES ASK...

What's the difference between weather and climate?

Weather describes the conditions of the atmosphere at a given place and time whereas *climate* is the long-term average of weather. For example, the expected weather conditions on a particular day will help you determine if you'll wear shorts or thermal underwear that day; the ratio of shorts to thermal underwear in your drawer reflects the climate of the region. Or, as Mark Twain once said about the difference between the two, "Climate is what we expect, weather is what we get."

The major components of Earth's climate system are shown in Figure 16.1. Notice that the oceans are the most massive part of Earth's climate system.

Planetary atmospheric processes are large scale and include many **feedback loops**, which are processes that modify the end result. For example, warmer surface temperatures increase evaporation rates. This in turn increases water vapor in the atmosphere, which absorbs heat emitted from Earth's surface before it gets released into space. Therefore, the more water vapor in the air, the less heat escapes and the warmer the planet becomes. This type of feedback loop is called a *positive-feedback loop* because it reinforces the initial change.

Alternatively, *negative-feedback loops* tend to counteract or mitigate an initial change. One such example is the formation of clouds. A probable result of a global temperature rise is an accompanying increase in cloud cover due to the higher moisture content of the atmosphere. Most clouds are good reflectors of incoming solar energy, thus diminishing the amount of solar energy available to heat Earth's surface and warm the atmosphere. In this way, clouds can cause a decrease in overall air temperature.

These two examples of increased water vapor in the atmosphere show that it can be both a positive-feedback loop and a negative-feedback loop. Which effect, if either, is stronger? Recent studies show that the negative effect of higher reflectivity is dominant. Therefore, the net result of an increase in atmospheric moisture should be a decrease in air temperature. The magnitude of this negative-feedback loop, however, is not likely to be as great as the feedback caused by other positive feedback loops between other parts of Earth's climate system. Thus, although increases in atmospheric moisture and cloud cover may partly offset a global temperature increase, climate models show that the overall effect will still be a temperature increase. In fact, the scientific consensus is that the increasing levels of

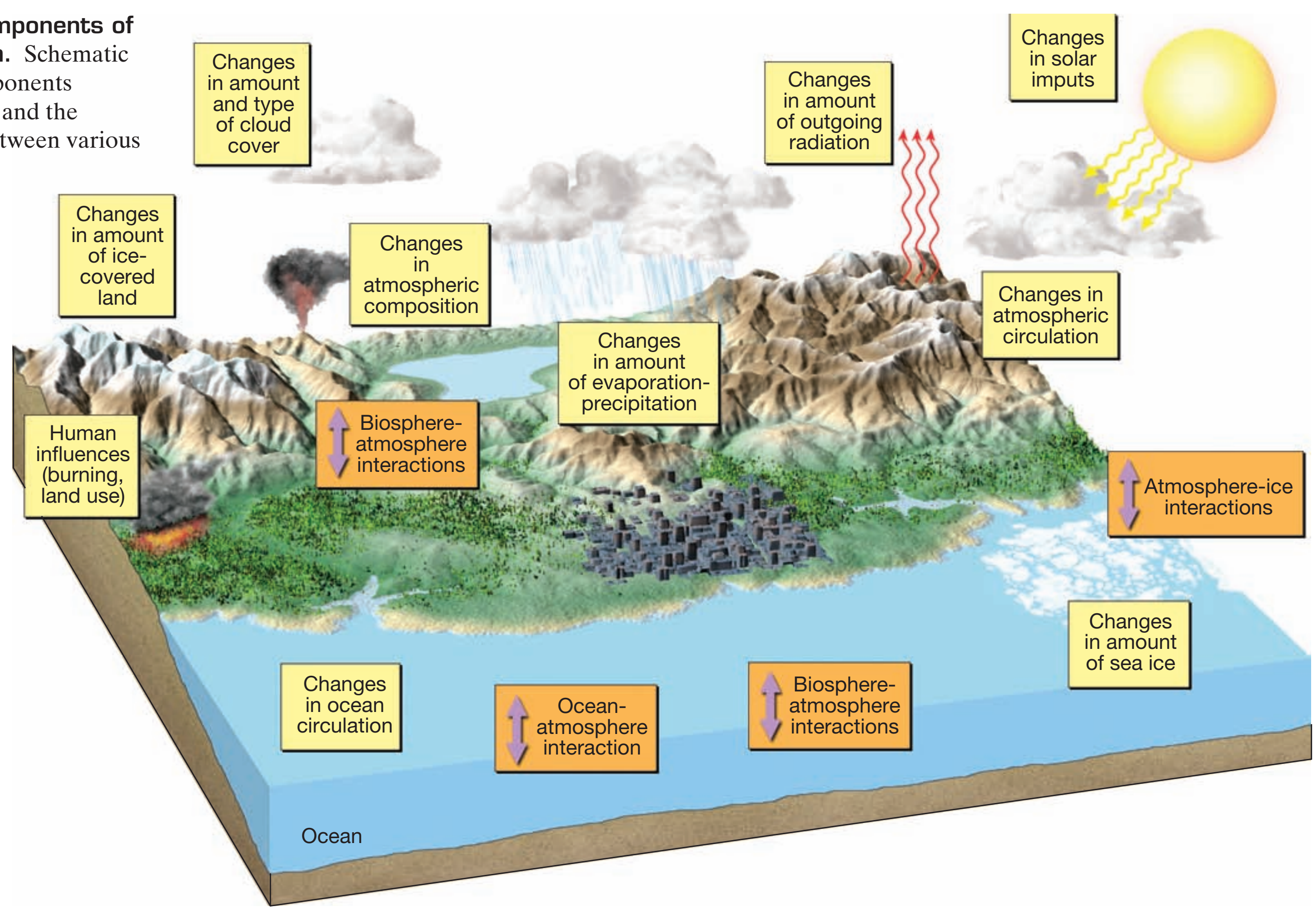


FIGURE 16.1 Major components of Earth's climate system. Schematic view showing major components of Earth's climate system and the interactions that occur between various components.

human-caused[2] emissions will lead to a warmer planet with a different distribution of climate patterns than what currently exist on Earth.

The global climate system contains many feedback loops, such as the role of clouds at different altitudes, the presence of fine atmospheric particles called *aerosols*, the shading effect from air pollution, heat uptake by the oceans, and the addition of water vapor in the atmosphere. Many of these feedback loops influence other feedbacks. For example, some computer models of climate show that if Earth's climate does warm as anticipated, there will be more evaporation of seawater, thus using up much of the excess heat and generating more cloud cover, which will block the Sun's rays and significantly reduce the warming effect. As such, the successful modeling of Earth's climate and its feedback loops is one of the biggest scientific challenges today—even using some of the world's most powerful computers.

KEY CONCEPT
Earth's climate system consists of exchanges of energy and moisture between the atmosphere, hydrosphere, geosphere, biosphere, and cryosphere. The global climate system contains many complex feedback loops.

16.2 Earth's Recent Climate Change: Is It Natural or Caused By Human Influence?

Records of past climate change reveal that natural events have influenced climate throughout Earth's history. Skeptics of global climate change point out that because Earth's climate has fluctuated in the past, the recent climate change observed on Earth could be a natural event. How can scientists tell whether this is true?

Determining Earth's Past Climate: Proxy Data and Paleoclimatology

Climate scientists use three closely connected methods to understand changes in Earth's climate: They look at records of Earth's past climates to see how and why climate changed in the past; they build computer models that allow them to see how the climate works; and they closely monitor Earth's current vital signs with an array of instruments ranging from space-based satellites to deep-sea thermometers. These monitoring tools, however, have been available for only a few decades. To understand the behavior of the atmosphere and to anticipate future climate change, scientists must be able to discern how climate has changed in the past.

Instrumental records go back only a couple of centuries at best, and the further back we go, the less complete and more unreliable the data become. To overcome the lack of direct measurements in the past, scientists must decipher and reconstruct Earth's previous climates using indirect evidence. Such **proxy** (*proxum* = nearest) data come from natural recorders of climate variability such as sea floor sediments (see Chapter 4), coral deposits, annual layers of snow packed in glacial ice (Figure 16.2), fossil

FIGURE 16.2 Researchers extract an ice core from its drilling tube. To reconstruct past temperatures and atmospheric conditions, scientists use natural records of climate change such as this ice core that was recently collected in Antarctica. The annual layers of snow packed in glacial ice preserve a record of climate that stretches back hundreds of thousands of years.

[2]Human-caused influence is also known by the term *anthropogenic* (*anthro* = human, *generare* = to produce).

pollen, tree-growth rings, and even historical documents. The data is cross-checked between the various methods and also matched with recent instrumental measurements (where overlap exists) to ensure accuracy. Scientists who analyze proxy data and reconstruct past climates are engaged in the study of **paleoclimatology** (*paleo* = ancient, *climate* = climate, *ology* = the study of). The main goal of such work is to understand Earth's past climate in order to gain insight into Earth's current and future climate. For example, climatologists have identified both warmer and cooler periods in Earth's recent past, such as the Medieval Warm Period (approximately 950–1250 A.D.) and the Little Ice Age (approximately 1400–1700 A.D.). As we will see, climatologists have used proxy data to construct a detailed history of Earth's climate that extends back in time over the past several hundred thousand years.

Natural Causes of Climate Change

Natural factors that affect Earth's climate include changes in solar energy, variations in Earth's orbit, volcanic eruptions, and even the movement of Earth's tectonic plates. Let's examine how each of these factors affects global climate.

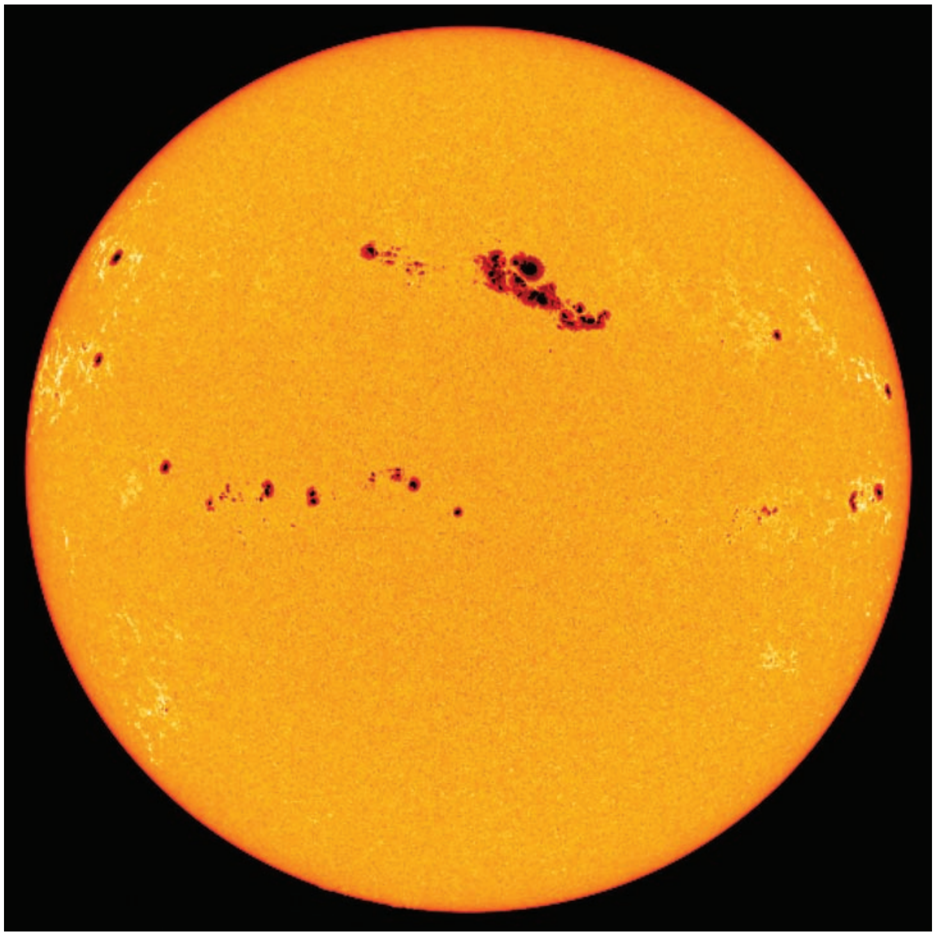


FIGURE 16.3 Sunspots. The dark blemishes on this image of the Sun are called sunspots, which are actually huge magnetic storms. The occurrence of sunspots varies in an 11-year cycle, which does not correlate with recent climate changes on Earth.

CHANGES IN SOLAR ENERGY Among the most persistent hypotheses of climate change have been those based on the idea that the Sun is a variable star, and its output of energy varies through time. In essence, increases in solar output cause global warming, while reductions in solar energy result in global cooling. This notion is appealing because it can be used to explain climate change of any length or intensity. However, an increase in solar output also falls short of explaining recent warming. Earth-orbiting satellites have been making precise measurements of the Sun's output since the 1980s, and while the Sun's luminosity has increased by a small amount (0.04%), the observed changes were not large enough to account for the warming recorded during the same period. Even proxy data of solar brightness over the past 1000 years does not show a correlation with changes in climate.

Several proposals for climate change are based on solar variability related to **sunspots**, which are dark blemishes that occur periodically on the Sun's surface (Figure 16.3). Sunspots are huge magnetic storms that extend from the Sun's interior to its surface and are associated with the Sun's ejection of particles. These particles can disrupt satellite communications but also produce the *aurora* (*Aurora* = Roman goddess of dawn), which is a phenomenon caused by charged solar particles that interact with Earth's magnetic field and produce lights in the sky. In the Northern Hemisphere, these lights are known as the *aurora borealis*, or *northern lights*, and they have a matching component in the Southern Hemisphere, called the *aurora australis*, or *southern lights*.

Along with other solar activity, the numbers of sunspots seems to increase and decrease in a regular way, creating a cycle of about 11 years that has been observed since the 1700s. The last solar maximum occurred in 2001; the magnetically active sunspots at that time produced powerful solar flares that caused large geomagnetic disturbances and disrupted some space-based technology on Earth. In spite of efforts to correlate this cycle of sunspot activity to temperature and precipitation changes on Earth, there is no clear evidence to support it. In fact, many studies have shown that there is no significant correlation between solar activity and climate on such short timescales.

VARIATIONS IN EARTH'S ORBIT Another natural mechanism of climate change involves changes in Earth's orbit. Changes in the shape of the orbit (*eccentricity*), variations in the angle that Earth's axis makes with the plane of its orbit (*obliquity*), and the wobbling of the axis (*precession*) cause fluctuations in the seasonal and latitudinal distribution of solar radiation reaching Earth (Figure 16.4). These variations have cycles of about 100,000 years, 41,000 years, and 26,000 years, respectively; when they coincide with one another, they tend to amplify each other and cause climate variations on Earth. This idea, first developed by Serbian astrophysicist Milutin Milankovitch, is called a *Milankovitch cycle*. It is now well established that these variations have contributed to the alternating glacial and interglacial episodes that characterize the most recent ice age, which occurred during the past few million years.

Although it is well established that Milankovitch cycles are responsible for long-term climate change associated with the most recent ice age on Earth, these changes take many thousands of years to manifest themselves. In contrast, the dramatic and rapid climate change that is occurring on our planet cannot be explained by these long-term variations in Earth's orbit.

VOLCANIC ERUPTIONS Explosive volcanic eruptions emit huge quantities of gases and fine-grained debris into the atmosphere (Figure 16.5). The largest eruptions are sufficiently powerful to inject material high into the atmosphere, where it spreads around the globe and remains aloft for many months or even years. As was seen with historic eruptions such as Mount Tambora in Indonesia (1815), Krakatoa in Indonesia (1883), El Chichón in Mexico (1982), and Mount Pinatubo in the Philippines (1991), volcanic material ejected into the atmosphere filters out a portion of the incoming solar radiation, which in turn cools the planet. For example, the year after the 1815 eruption of Mount Tambora became widely known as the Year without Summer because of its effect on North American and European weather. However, the gases emitted during a volcanic eruption react with other components of the climate system and the volcanic dust eventually settles out. Thus, the cooling effect of a single eruption, no matter how large, is relatively small and short-lived.

If volcanism is to have a pronounced impact over an extended period, many great eruptions closely spaced in time would need to occur. If this happened, the upper atmosphere would be loaded with enough gases to alter the composition of the atmosphere and enough volcanic dust to seriously diminish the amount of solar radiation reaching the surface. Because no such period of explosive volcanism is known to have occurred in historic times, it is unlikely to be responsible for the recent observable climate changes. In the distant past, however, it may have been influential in contributing to climate shifts.

MOVEMENT OF EARTH'S TECTONIC PLATES As described in Chapter 2, Earth's tectonic plates have moved great distances. During the geologic past, plate movements have accounted for many dramatic climate changes as landmasses shifted in relation to one another and moved to different latitudinal positions. As land masses have moved, they have changed ocean circulation,

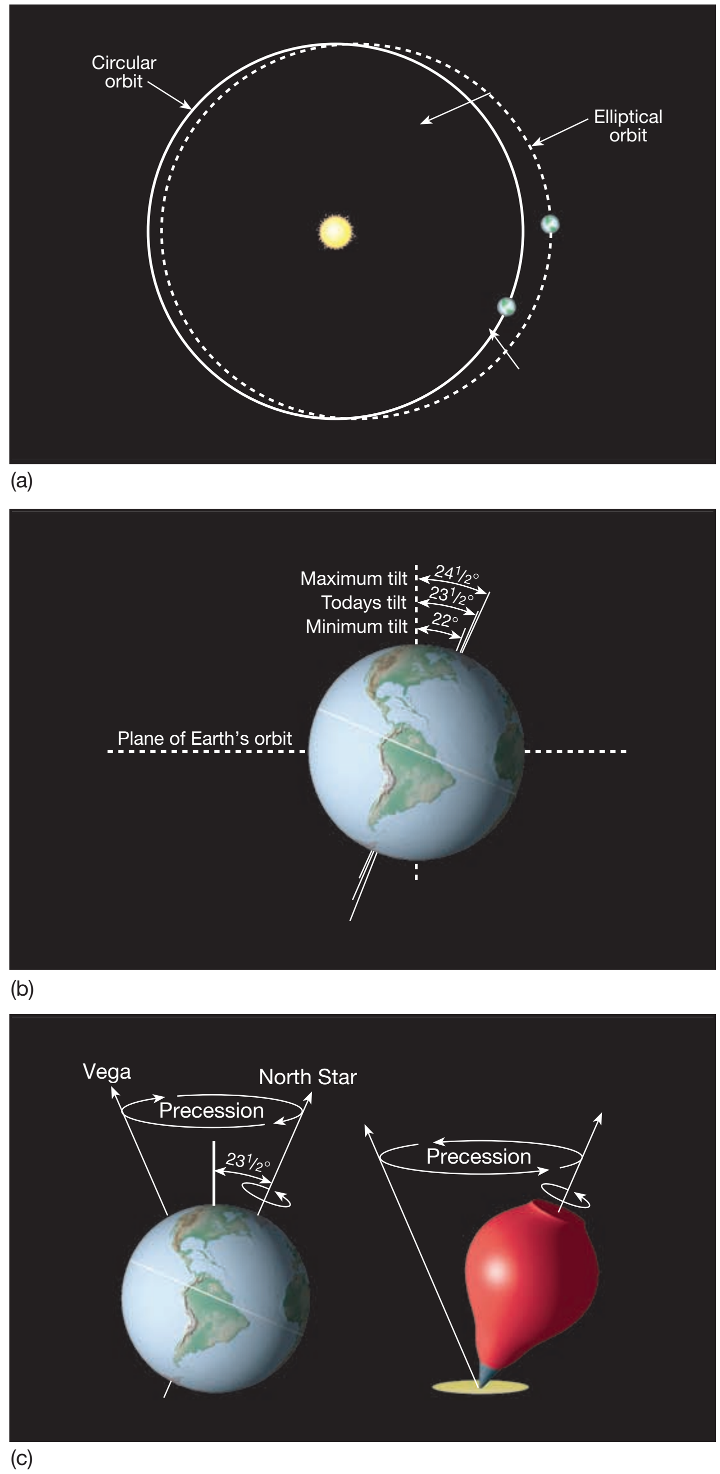


FIGURE 16.4 Variations in Earth's orbit. **(a)** The shape of Earth's orbit (*eccentricity*) gradually changes from nearly circular to one that is more elliptical and then back again during a cycle of about 100,000 years (note that Earth's elliptical orbit is greatly exaggerated in this figure). **(b)** The tilt of Earth's axis of rotation with respect to the plane of Earth's orbit (*obliquity*) varies from 21.5° to 24.5° during a cycle of about 41,000 years (currently, Earth's tilt is 23.5°). **(c)** Earth's axis wobbles like that of a spinning top (*precession*); as a result, the axis points to different spots in the sky during a cycle of about 26,000 years.

FIGURE 16.5 Volcanic eruptions spew volcanic debris and gases into the atmosphere. This 1991 eruption of Mount Pinatubo in the Philippines shows that volcanoes have the ability to inject into the atmosphere large quantities of volcanic dust and gases, which can circle the globe and block incoming solar radiation, thereby cooling the planet.

altering the transport of heat and moisture and consequently the climate. For example, the opening of Drake Passage between South America and Antarctica about 41 million years ago caused a fundamental reorganization of ocean currents in the Southern Hemisphere, leading to the isolation of Antarctica, which caused it to become much cooler and develop a permanent ice cap. However, the rate of plate movement is very slow—only a few centimeters per year—and so appreciable changes in the positions of continents occur only over great spans of geologic time. Thus, climate changes triggered by shifting plates are extremely gradual and happen on a scale of millions of years.

CAN NATURAL CLIMATE CHANGE FACTORS EXPLAIN RECENTLY OBSERVED CLIMATE CHANGES? It is clear that natural factors have changed Earth's climate in the past and that they will undoubtedly change it in the future. For example, natural climate change has been definitively linked to global climate shifts such as the Pleistocene Ice Age, the Medieval Warm Period, and the Little Ice Age. However, an examination of natural climate change factors reveals that the recently observed climate changes such as the rate of warming in recent decades is greater than can be explained by any natural factors. In fact, several recent studies based on paleoclimate data reveal that the warming in the past three decades is unprecedented on Earth during the past 1000 years. The only viable explanation for these recent climate changes including warming of Earth's surface is the well-documented increase in human-caused emissions.

The IPCC: Documenting Human-Caused Climate Change

In 1988, the United Nations Environment Programme and the World Meteorological Organization sponsored the **Intergovernmental Panel on Climate Change (IPCC)**, a worldwide group of atmospheric and climate scientists that began studying the human effects on climate change and global warming. The IPCC utilizes peer-reviewed literature to analyze all aspects of climate change—including science, impacts, adaptation, and mitigation—to provide independent scientific advice about climate change. Since 1990, the group has published a series of assessment reports (Figure 16.6) that are highly regarded by both scientists and policymakers and have sparked international movement on climate change.

The IPCC's first assessment report, released in 1990, became the basis for the United Nations Framework Convention on Climate Change, an international treaty in which signatories agreed to the idea of reducing concentrations of greenhouse gases in the atmosphere. The IPCC's second assessment report, published in 1995, states that "the balance of evidence suggests a discernable human influence on global climate" and that global warming "is unlikely to be entirely due to natural causes."

In 2001, a third IPCC assessment report was published under the guidance of 426 scientists and was unanimously accepted by more than 160 delegates from 100 countries. The report states: "There is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities." The report notes that recent regional climate changes already have affected many physical and biological systems on Earth and that projected climate change—as well as changes in climate extremes—could have major consequences. The report also revised the estimate of the world's expected temperature increase for the period between 1990 and 2100. Previously, the amount of predicted warming had been 1.0 to 3.5°C (1.8 to 6.3°F); the new report revised it upward at 1.4 to 5.8°C (2.5 to 10.4°F), based on new climate models.

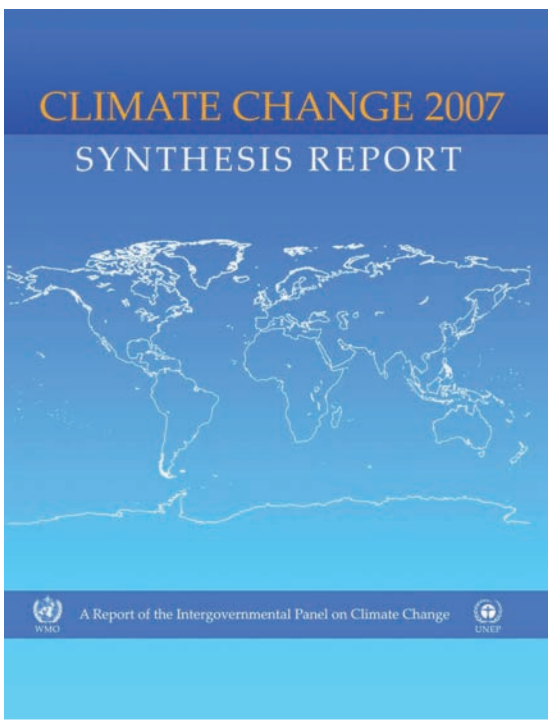


FIGURE 16.6 Cover of the IPCC Climate Change 2007 Synthesis Report. The Intergovernmental Panel on Climate Change (IPCC) has published four assessment reports since 1990 confirming that human-induced emissions are altering Earth's climate.

In 2005, an international consortium of science academies, including the U.S. National Academy of Sciences, issued this statement: "The scientific understanding of climate change is now sufficiently clear to justify nations taking prompt action . . . . As the United Nations Framework Convention on Climate Change (UNFCCC) recognizes, a lack of full scientific certainty about some aspects of climate change is not a reason for delaying an immediate response that will, at a reasonable cost, prevent dangerous [human-induced] interference with the climate system."

In 2007, a fourth IPCC assessment report—created by more than 600 authors from 40 countries and reviewed by more than 600 individuals—was published. The report was accepted and approved by representatives from 113 countries. The fourth IPCC report confirmed what many scientists had long suspected: Human-caused climate change is already altering Earth. In fact, *climate change models can mimic present-day conditions only if human emissions are taken into account*. Some of the documented changes specifically mentioned in the report include the warming of oceans and land, temperature extremes, melting of snow and ice, changing wind patterns, changing water patterns, and a variety of changes to a large assortment of organisms. The report also states that the temperature increases observed since the mid-20th century are very likely due to human-caused emissions, with the probability of human influence upgraded to greater than 90% certainty. This IPCC report clearly documents the fact that by adding emissions to the atmosphere, humans are altering global climate and are producing significant impacts on physical and biological systems worldwide. A fifth IPCC assessment report is expected to be published in 2014.

The IPCC assessment reports provide strong documentation of the planet's human-induced climate changes, such as global warming. In recognition of that fact, the IPCC was named a co-recipient of the 2007 Nobel Peace Prize, along with former U.S. Vice President Al Gore, Jr., for his work on the documentary film *An Inconvenient Truth*. When it bestowed the award, the Nobel Committee noted, "Through the scientific reports it has issued over the past two decades, the IPCC has created an ever-broader informed consensus about the connection between human activities and global warming."

Other subsequent reports confirm the findings of the IPCC. In 2009, for example, the U.S. Global Change Research Program issued a 190-page interagency report entitled "Global Climate Change Impacts in the United States." The report states that "global warming is unequivocal and primarily human-induced." The report also notes that "global average temperature has risen by about 1.5°F [0.8°C] since 1900. By 2100, it is projected to rise another 2 to 11.5°F [1.1 to 6.4°C]. Increases at the lower end of this range are more likely if global heat-trapping gas emissions are cut substantially. If emissions continue to rise at or near current rates, temperature increases are more likely to be near the upper end of the range." The report warns that climate change will have numerous impacts on water resources, ecosystems, agriculture, coastal areas, human health, and other sectors.

STUDENTS SOMETIMES ASK . . .

Why was this winter so cold when there's supposed to be global warming?

One of the documented changes of a warmer world is increased variation in temperature extremes. This means that while the climate is warming, there will be a wider range of temperatures, including both warmer and colder temperature extremes. In essence, global warming increases the chances of such extreme events occurring. Also, remember that climate is the long-term average of weather, so although it might be colder during one season, the climate can still be warming. What matters is not what happens on any given day or season but what the trend is over a period of years. On this, the data are clear: Earth is experiencing long-term global warming.

KEY CONCEPT

Earth's climate has changed in the past due to natural causes such as changes in the Sun's output, variations in Earth's orbit, volcanic activity, or the movement of tectonic plates. Multiple lines of evidence show that the current climate changes are due primarily to human activities that release heat-trapping emissions into the atmosphere.

16.3 What Causes the Atmosphere's Greenhouse Effect?

There is ample documentation that human-caused emissions are responsible for the recent and dramatic climate changes experienced on Earth. One such change is the increase in average worldwide temperature, which is called **global warming**. Although the warming of Earth's surface and atmosphere is a natural process controlled by the greenhouse effect, it is also being altered by human emissions, a phenomenon that is often referred to as the *anthropogenic greenhouse load* or the *enhanced greenhouse effect*.

The **greenhouse effect** gets its name because it keeps Earth's surface and lower atmosphere warm in a way similar to a greenhouse that keeps plants warm

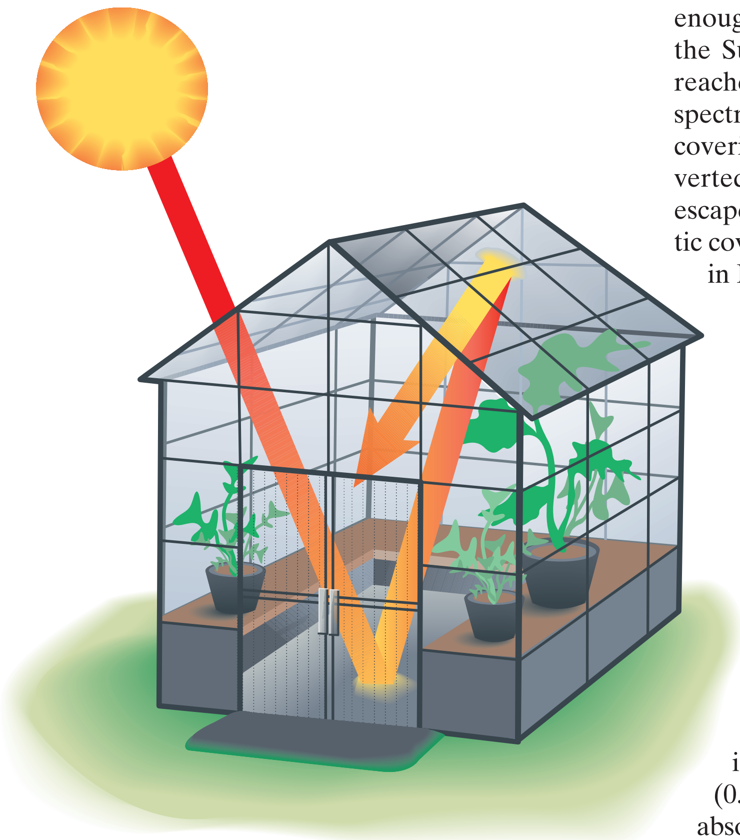


FIGURE 16.7 How a greenhouse works. The glass of a greenhouse allows incoming sunlight to pass through but traps heat. Similarly, gases like water, carbon dioxide, and methane in Earth's atmosphere act just like the glass of a greenhouse by allowing sunlight to pass through but trapping heat.

Global Warming

STUDENTS SOMETIMES ASK...

What would Earth's temperature be like if there was no natural greenhouse effect?

In a word: *freezing*! The worldwide average temperature of Earth and the lowermost atmosphere (troposphere) is about 15°C (59°F). If the atmosphere contained no heat-trapping greenhouse gases, the average worldwide temperature would be about −18°C (0°F). At this temperature, our planet would very likely have a frozen surface akin to that of Mars. Instead, the atmosphere's greenhouse gases help create and sustain the moderate temperatures that make Earth habitable.

enough to grow regardless of outside conditions (Figure 16.7). Energy radiated by the Sun covers the full electromagnetic spectrum, but most of the energy that reaches Earth's surface is short wavelengths, in and near the visible portion of the spectrum. In a greenhouse, shortwave sunlight passes through the glass or plastic covering, where it strikes the plants, the floor, and other objects inside and is converted into longer-wavelength infrared radiation (heat). Some of this heat energy escapes from the greenhouse and some is trapped for a while by the glass or plastic covering, which keeps the greenhouse nice and snug—much like what happens in Earth's atmosphere.[3]

Earth's Heat Budget and Changes in Wavelength

Figure 16.8 diagrams the various components of Earth's **heat budget**, which describes all the ways in which heat is added to and subtracted from Earth. In the upper atmosphere, most solar radiation within the visible spectrum penetrates the atmosphere to Earth's surface, like sunlight coming through greenhouse glass. After scattering by atmospheric molecules and reflection off clouds, about 47% of the solar radiation that is directed towards Earth is absorbed by the oceans and continents. About 23% is absorbed by the atmosphere and clouds, and about 30% is reflected into space by atmospheric backscatter, clouds, and Earth's surface.

Figure 16.9 shows that most of the energy coming to Earth from the Sun is within the visible spectrum and peaks at a wavelength of 0.48 micrometer[4] (0.0002 inch). The atmosphere is transparent to much of this radiation, but it is absorbed by materials such as water and rocks at Earth's surface. These surface materials absorb and then emit radiation away from Earth's surface toward space as longer wavelength infrared (heat) radiation, with a peak at a wavelength of 10 micrometers (0.004 inch). Molecules of atmospheric gases such as water vapor, carbon dioxide, and other gases intercept the heat radiation that attempts to leave the planet, thus heating the atmosphere. This heating of the atmosphere is known as the greenhouse effect. Because Earth has maintained a relatively constant average temperature over long periods of time, the rates of energy absorption and reradiation back into space must be equal.

In summary, most of the solar radiation that is not reflected back to space passes through the atmosphere and is absorbed at Earth's surface. Earth's surface, in turn, emits longer wavelength infrared radiation (heat). A portion of this energy is absorbed by certain heat-trapping gases in the atmosphere, thus producing the greenhouse effect. Thus, *the change of wavelengths from visible to infrared is the key to understanding how the greenhouse effect works*.

Some of the infrared energy absorbed in the atmosphere becomes reabsorbed by Earth to continue the process; the rest is lost to space. The solar radiation received at the surface is therefore retained for a time within our atmosphere, where it moderates temperature fluctuations between night and day and also between seasons.

Which Gases Contribute to the Greenhouse Effect?

Earth's greenhouse effect is caused by an array of atmospheric gases, many of which have both natural and human-caused sources. Take, for example, water vapor, which contributes more to the greenhouse effect than any other gas. In

[3] Recent studies have indicated that an additional factor in keeping a greenhouse warm is that the greenhouse covering prevents mixing of air inside with cooler air outside. Although this is different from how the atmosphere works, the term *greenhouse effect* is still commonly used to describe the atmosphere's warming process.

[4] A micrometer (μm), or micron, is one-millionth of a meter.

fact, water vapor is the single most important absorber of heat—its contribution to the greenhouse effect is between 36% and 66% of the greenhouse effect—and together with clouds comprises between 66% and 85% of the greenhouse effect. Mostly, though, water vapor enters the atmosphere through evaporation and by other natural processes. Although atmospheric water vapor concentrations fluctuate regionally, studies suggest that human activity does not significantly affect water vapor concentrations except at local scales, such as near irrigated fields. And even then, the water vapor does not stay in the atmosphere for very long. In essence, human activities do not directly affect the amount of water vapor in the atmosphere on a global scale.

Table 16.1 shows the concentration of **greenhouse gases**—so called because of their heat-trapping capacity—that have been increasing as a result of human activities. Remarkably, these gases exist in very small amounts in the atmosphere, yet they have a profound effect on heating. Some of these greenhouse gases are released by both human and natural sources (such as carbon dioxide, which has been a component of the atmosphere long before human activities). Others, however, have no natural source and thus are clearly human induced (such as the chemicals known as chlorofluorocarbons).

Of all the human-caused gases, carbon dioxide makes the greatest relative contribution to increasing the greenhouse effect (Table 16.1). Carbon dioxide enters the atmosphere as the result of combustion of carbon compounds with oxygen and is a colorless and odorless gas that is the same one we exhale from our lungs. The conversion of **fossil fuels** (oil and natural gas) into energy by cars, factories, and power plants accounts for the majority of the annual human contribution to carbon dioxide emissions, with industrialized nations contributing the most. As a result of human activities, therefore, atmospheric concentration of carbon dioxide has increased nearly 40% over the past 250 years (Figure 16.10). What concerns scientists is that over the past 250 years—and especially in the past 50 years—human activities have been responsible for raising the concentration of greenhouse gases in the atmosphere at an ever-increasing rate. The concentration of atmospheric carbon dioxide is currently 387 parts per million and is increasing by about 2 parts per million each year; this rate of increase is double that from only 50 years ago. In terms of sheer numbers, humans are now pumping into the atmosphere more than 8 billion metric tons (8.8 billion short tons) of carbon dioxide each year.[5]

Methane is the second most abundant human-caused greenhouse gas (Table 16.1). It is produced by leakage from decomposing trash in landfills, by methane-belching domestic cattle, and by agriculture (particularly the cultivation of rice). Even though methane has a lower concentration in the atmosphere than carbon dioxide, it has a greater ability to produce warming on a per-molecule basis. Since the industrial revolution began in about 1750, the concentration of methane in the atmosphere has increased by 250%.

In 2005, researchers recovered a nearly 3.2-kilometer (2-mile) continuous ice core from Antarctica that contains a record of past atmospheric concentrations of

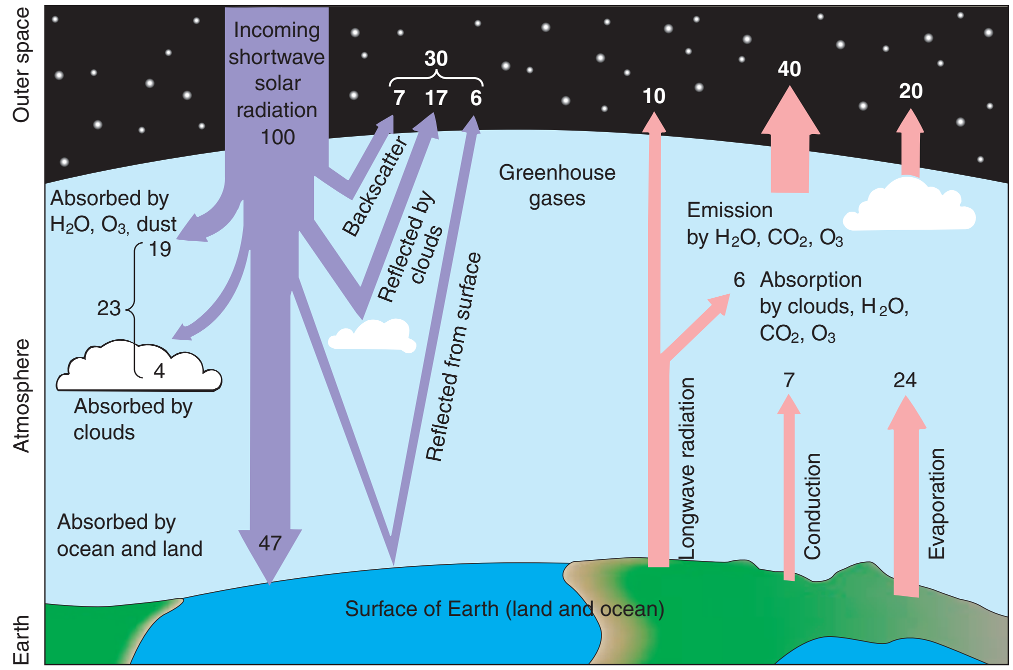


FIGURE 16.8 Earth's heat budget. One hundred units of shortwave solar radiation from the Sun (mostly visible light) are reflected, scattered, and absorbed by various components of the Earth–atmosphere system. The absorbed energy is radiated back into space from Earth as longwave infrared radiation (heat). If this infrared radiation does not leave Earth, global warming will occur.

web animation
Atmospheric Energy Balance

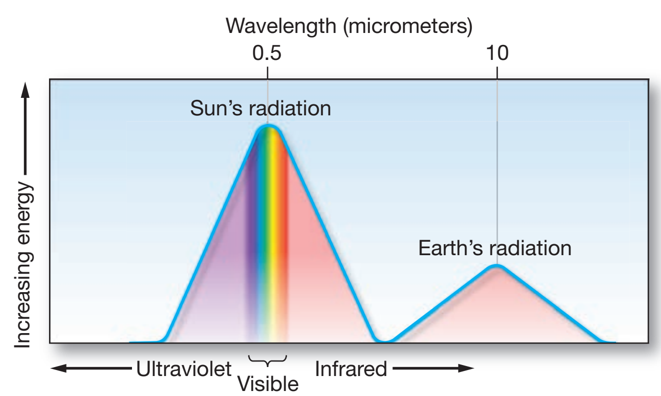


FIGURE 16.9 Energy radiated by the Sun and Earth. The intensity of energy radiated by the Sun peaks at a wavelength of 0.48 micrometer (0.0002 inch), which is in the visible part of the spectrum. Some of this energy is absorbed or reflected while some reradiates from Earth in the infrared (heat) range at a wavelength of 10 micrometers (0.004 inch).

[5]On average, each person on Earth emits more than 1 metric ton (1.1 short tons) of carbon dioxide per year. Of course, this number is several times greater for those living in industrial nations than for those living in developing countries.

TABLE 16.1 HUMAN-CAUSED GREENHOUSE GASES AND THEIR CONTRIBUTION TO INCREASING THE GREENHOUSE EFFECT

Atmospheric gas	Human-caused sources of gas	Pre-industrial (circa 1750) concentration (ppbv[a])	Present concentration (ppbv[a])	Current rate of increase or decrease (% per year)	Relative contribution to increasing the greenhouse effect (%)	Infrared radiation absorption per molecule (number of times greater than CO_2)
Carbon dioxide (CO_2)	Combustion of fossil fuels	280,000	387,0000	+0.5	60	1
Methane (CH_4)	Leakage, domestic cattle, rice agriculture	700	1750	+1.0	15	25
Nitrous oxide (N_2O)	Combustion of fossil fuels, industrial processes	270	315	+0.2	5	200
Tropospheric ozone (O_3)	Byproduct of combustion	0	10–80	+0.5	8	2000
Chlorofluorocarbon (CFC-11)	Refrigerants, industrial uses	0	0.26	−1.0	4	12,000
Chlorofluorocarbon (CFC-12)	Refrigerants, industrial uses	0	0.54	0.0	8	15,000
Total					100	

[a]ppbv = parts per billion by volume (not by weight).

STUDENTS SOMETIMES ASK...

Isn't carbon dioxide causing the hole in the ozone layer?

Here's the short answer: Definitely not! The ozone layer occurs within the atmosphere's stratosphere and is composed of ozone molecules (O_3) that absorb most of the Sun's ultraviolet radiation. Without it, unhealthy levels of ultraviolet radiation would reach Earth's surface, making the planet largely uninhabitable. The main ozone hole (actually, a seasonal thinning of the ozone layer) occurs above the South Pole, with a smaller one above the North Pole. Both are caused by chemical reactions with natural and human-generated compounds, particularly the now-banned chemicals CFC-11 and CFC-12, but not carbon dioxide. CFCs are also strong greenhouse gases (see Table 16.1), so CFCs are thus double threats to the environment: Their buildup in the atmosphere leads to the destruction of the ozone layer, and at the same time, contributes to global warming. Notice also from Table 16.1 that tropospheric (lower atmosphere) ozone, which is a byproduct of combustion, is a potent greenhouse gas. With the ban of CFCs firmly in place, scientists predict that the ozone layer will achieve its normal thickness by mid-century. However, new research reports that human-generated nitrous oxide, which destroys ozone, is now the single greatest ozone-depleting substance.

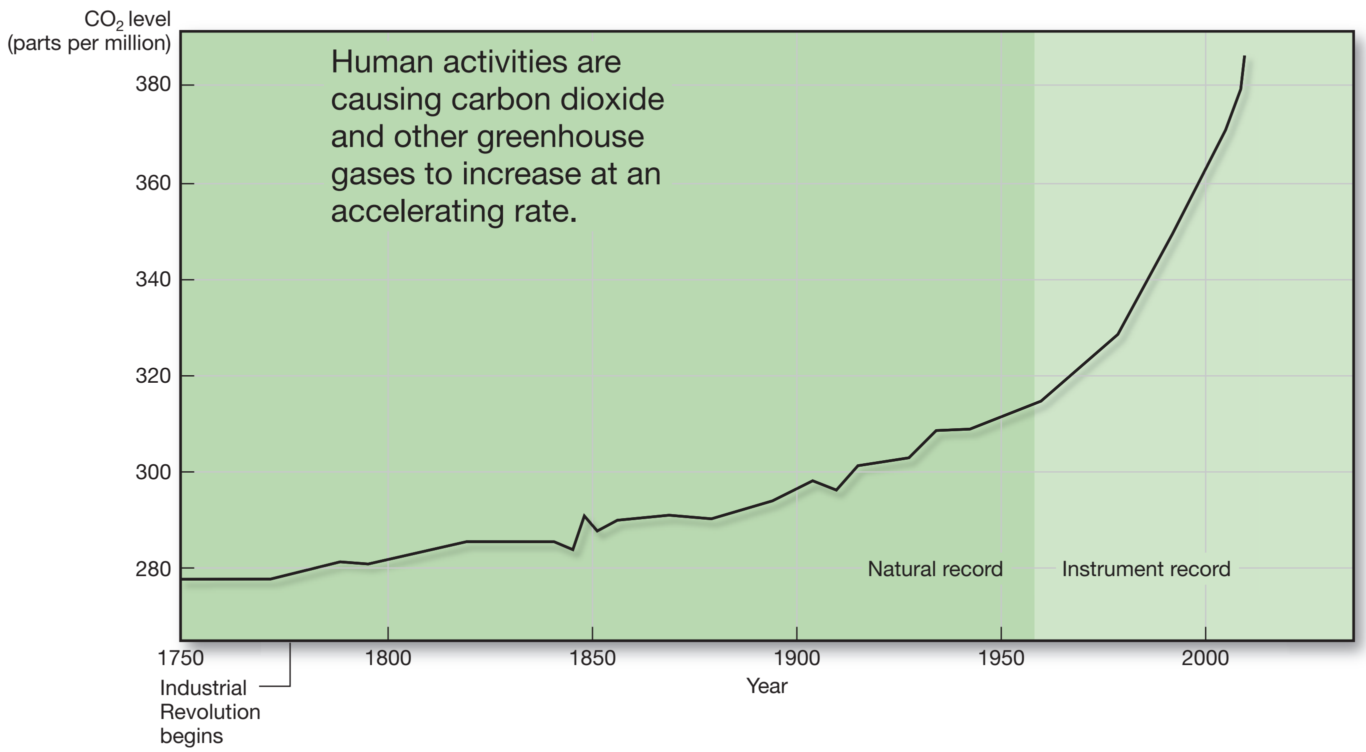


FIGURE 16.10 Amount of carbon dioxide in the atmosphere since 1750. There has been a dramatic increase of average worldwide atmospheric carbon dioxide since the Industrial Revolution began in the late 1700s. Values for 1958 to the present are from instrumental measurement of carbon dioxide at Mauna Loa Observatory in Hawaii; natural record values prior to 1958 are estimated from air bubbles in polar ice cores.

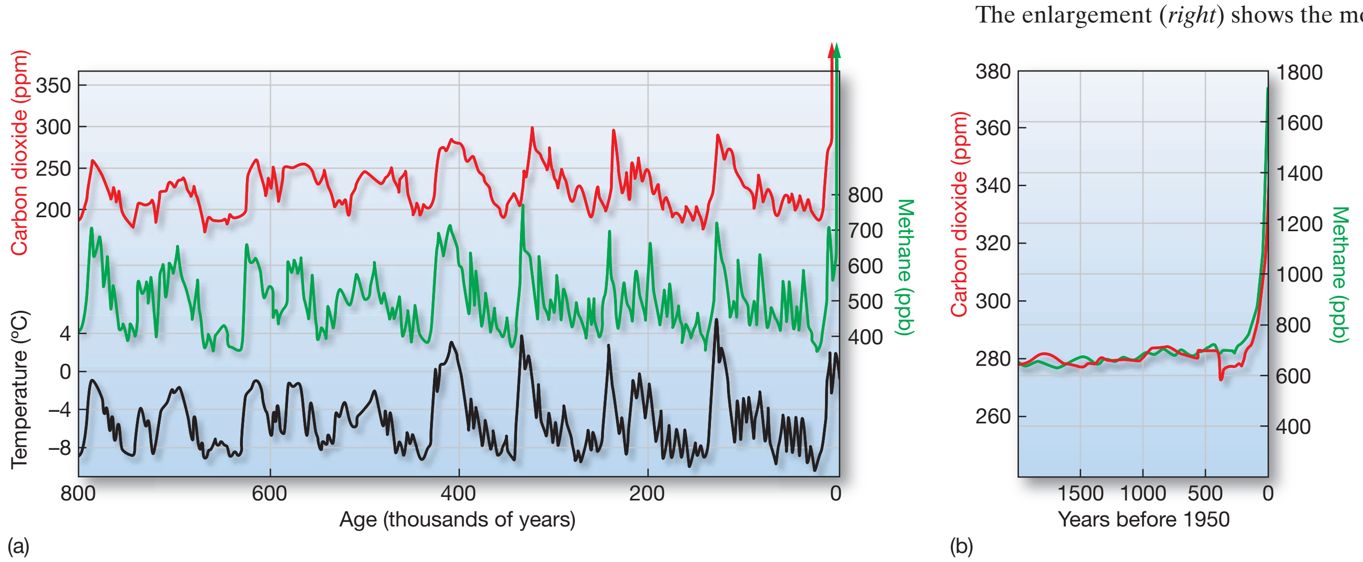
carbon dioxide and methane—two important greenhouse gases—that get trapped as the ice accumulates. Analysis of the core shows that current atmospheric concentrations of carbon dioxide and methane are at their highest levels in at least the past 800,000 years (Figure 16.11). In addition, the chemical make-up of the ice provides a proxy of the past average temperature on Earth, which shows a strong correlation with atmospheric methane and carbon dioxide.

The other trace gases shown in Table 16.1—nitrous oxide, tropospheric ozone, and chlorofluorocarbons—are present in far lower concentrations. Yet they are still very important because they absorb many times more infrared radiation per molecule than carbon dioxide or methane (Table 16.1, *last column*), thus making them very potent contributors to warming. Still, these gases have a smaller overall contribution to increasing the greenhouse effect because their concentrations are so low. Nevertheless, all of these gases must be taken into account when considering the total amount of greenhouse warming.

KEY CONCEPT

The greenhouse effect is caused by gases that allow sunlight to pass through but trap heat energy before it is radiated back to space. Carbon dioxide is foremost in an array of gases from human activity that increase the atmosphere's ability to trap heat.

FIGURE 16.11 Ice core data of atmospheric composition and global temperature. Antarctic ice core data for the past 800,000 years showing atmospheric carbon dioxide (*red curve*), methane (*green curve*), and average global temperature (*black curve*). Atmospheric composition is from analysis of trapped air bubbles in ice; temperature reconstruction is derived from the chemical make-up of the ice. The enlargement (*right*) shows the most recent 2000 years.



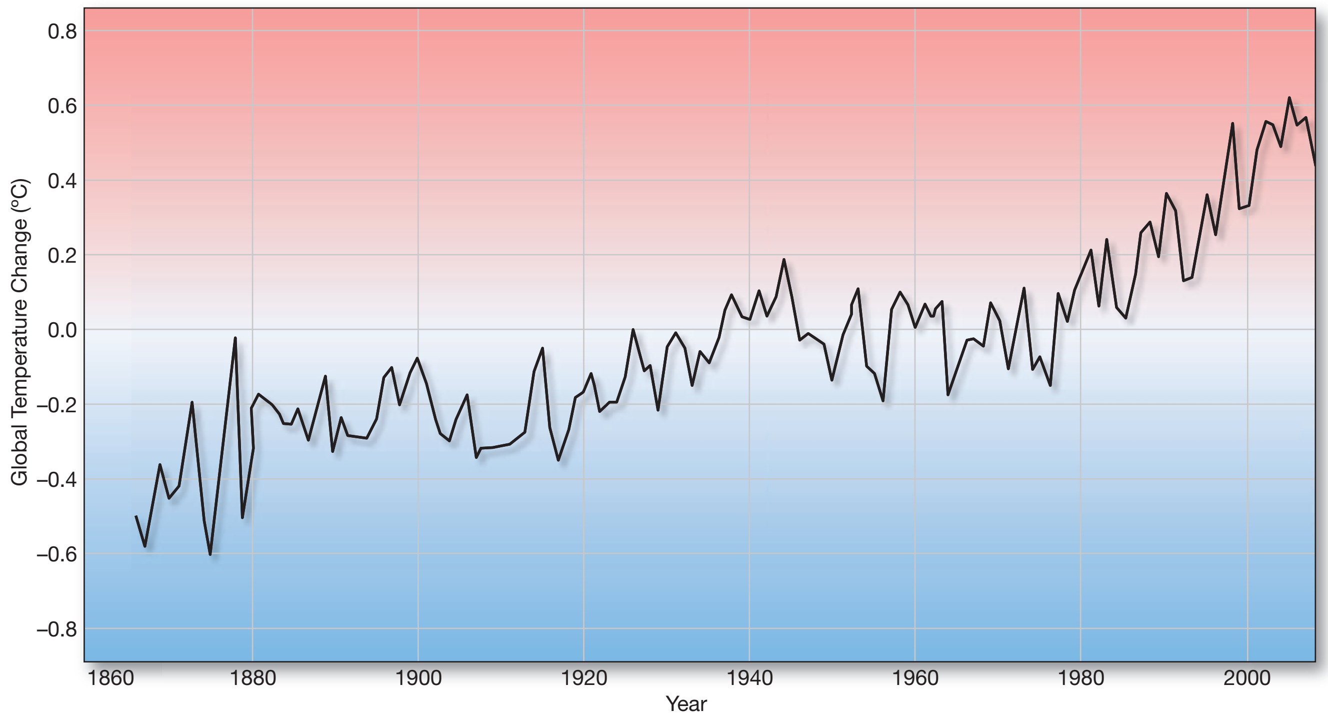


FIGURE 16.12 Instrumental temperature record since 1865. The record of global average surface air temperature from thermometer readings indicates a global warming of at least 0.8°C (1.4° F) over the past 140 years. The peaks and troughs indicate the natural year-to-year variability of climate.

What Changes Are Occurring Because of Global Warming?

Melting glaciers and ice caps, shorter winters, shifts in species distribution, and a steady rise in average global and sea surface temperatures are just some of the indications that additional human-induced greenhouse warming is occurring. Take, for example, these observations about Earth's temperature, which are based on weather stations on land, satellite data, and, for earlier measurements, proxy data or data from ships:

- Earth's average surface temperature has risen 0.6°C (1.1°F) over the past 30 years and 0.8°C (1.4°F) over the past 140 years (Figure 16.12).
- The rate of warming in the past 50 years was double the rate observed over the past 100 years.
- Worldwide, the 8 warmest years have all occurred since 1998, and the 14 warmest years on record have all occurred since 1990.
- Over the past century, the planet has experienced the largest increase in surface temperature in 1300 years.

Today, there is a scientific consensus that human-induced emissions are responsible for this observed warming. In fact, the warming trends observed since 1950 cannot be explained without accounting for human-caused greenhouse gases.

As global temperatures continue to increase, researchers use sophisticated climate models to forecast what changes will occur on Earth. Because of the complexity of the climate system and its feedback loops, not all models agree as to what or how severe those changes will be. However, there are points on which the models do agree: a strong warming of high northern latitudes, a moderate warming of middle latitudes, and relatively little warming in low latitudes. Other predicted changes—many of which are already happening—include the following:

- Earlier summertime seasons, with higher summer temperatures, including longer and more intense heat waves.
- More extreme precipitation events, such as severe droughts in certain areas and increased chances of flooding in other areas.
- The worldwide retreat of mountain glaciers, which is already being observed.

STUDENTS SOMETIMES ASK . . .

I've heard that scientists were predicting an oncoming ice age only a few decades ago. What's changed?

Skeptics of global warming have pointed out that in the 1970s, climate scientists were warning of an imminent ice age. In reality, the idea lacked scientific consensus, although the media popularized the notion with sometimes quite alarmist accounts. It is true that from the 1950s through the 1970s, there was an observed global cooling trend. This fact, coupled with the idea that ice ages are cyclical and that our planet was poised for millennia of global cooling based on variations in Earth's orbit, led to speculation that Earth may return to an ice age. However, it is now known that the recent cooling was probably due to a substantial increase in aerosols, which at the time masked the telltale signature of global warming. Looking at a longer view of global temperature since that time, Earth's recent warming trend can be clearly discerned.

- Water contamination issues that lead to larger outbreaks of waterborne infectious diseases such as malaria, yellow fever, and dengue fever.
- Shifts in the distribution of plant and animal communities that affect entire ecosystems and may drive certain species to extinction.

Note that not all predicted changes have negative consequences. For instance, increased warming is expected to provide a longer growing season for some crops, and increased atmospheric carbon dioxide should help promote productivity in plants. However, a number of uncertainties remain in understanding regional effects of climate change, and various components of the climate system may respond to these changes in unanticipated and surprising ways.

16.4 What Changes Are Occurring in the Oceans?

The oceans are a key component in the global climate system that is currently experiencing dramatic changes. Let's examine some of the observed and predicted effects of global warming in the oceans.

Increasing Ocean Temperatures

Studies have revealed that the oceans have absorbed the majority of the increased heat in the atmosphere. Indeed, millions of ocean temperature observations at various depths reveal that there has been an increase in surface temperature (Figure 16.13). These measurements indicate that global sea surface temperatures have risen by about 0.6°C (1°F) from global warming, mainly since about 1970. However, this warming has not been uniform throughout the ocean. The greatest temperature increases have been experienced in the Arctic Ocean, near the Antarctic Peninsula, and in tropical waters. Even deep waters are showing signs of warming: In some places, warming has been documented to a depth of 0.8 kilometer (0.5 mile) or more. To determine the extent of warming experienced in the oceans, scientists have initiated global monitoring of ocean temperature (Box 16.1).

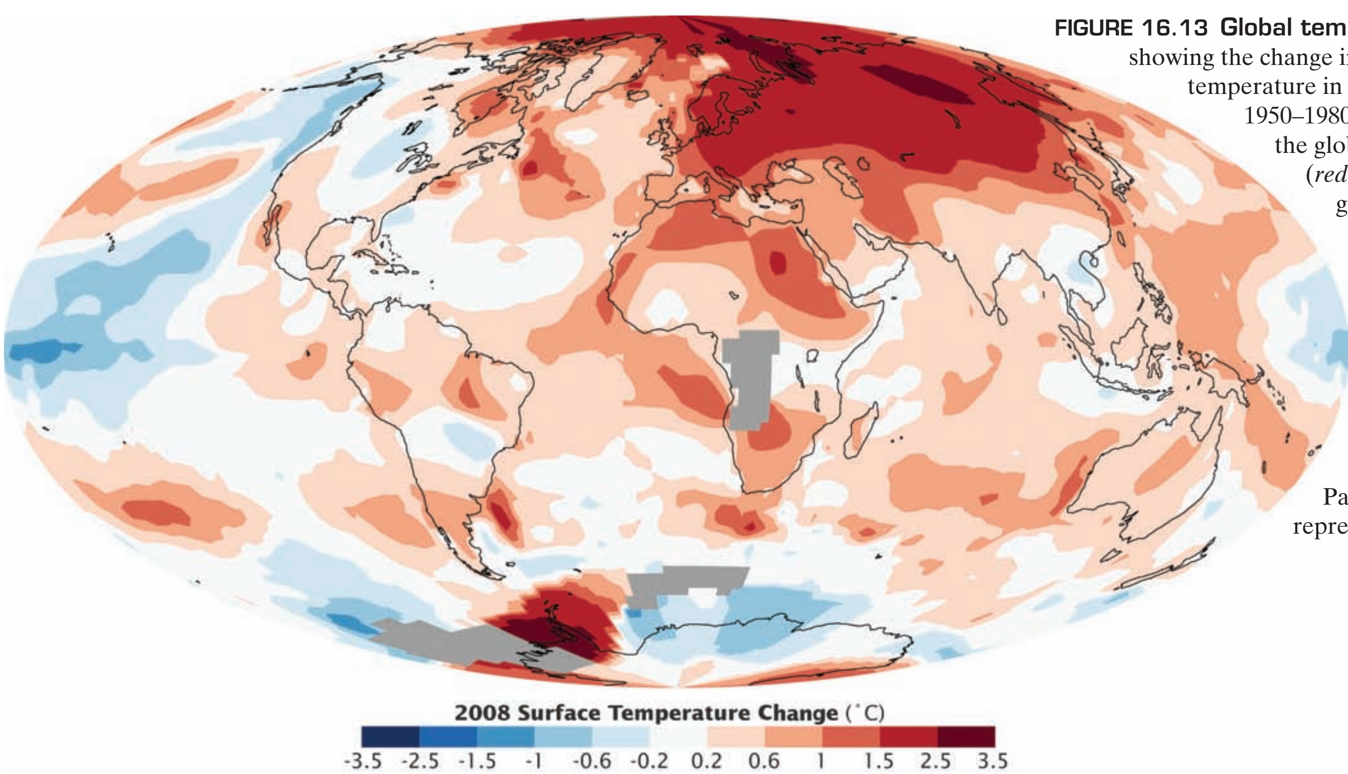


FIGURE 16.13 Global temperature change. Map showing the change in land and ocean surface temperature in 2008 compared to the 1950–1980 baseline period. Most of the globe is anomalously warm (*red areas*) as a result of greenhouse warming, with the greatest temperature increases in the Arctic Ocean, Siberia, the Antarctic Peninsula, and tropical regions. A persistent cool-water La Niña event (*blue area*) is affecting the values in the tropical Pacific Ocean. Gray areas represent no data.

16.1 FOCUS ON THE ENVIRONMENT

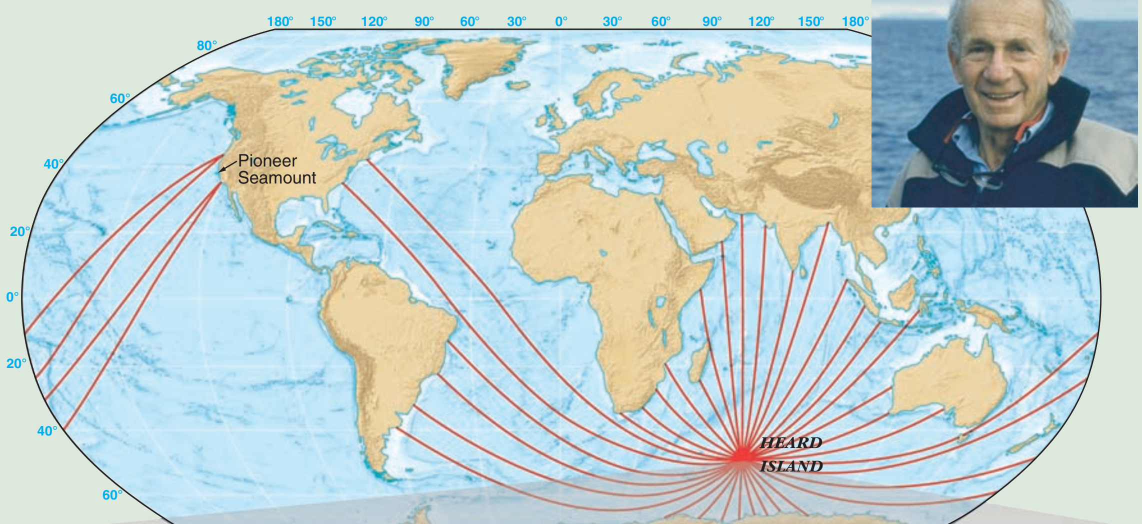
THE ATOC EXPERIMENT: SOFAR SO GOOD?

Worldwide, a layer exists in the ocean at a depth of about 1000 meters (3300 feet) formed by temperature and pressure conditions that cause sound originating above and below it to become refracted, or bent, into the layer (Figure 16A, *lower inset*). Once in this layer, called the *SOFAR channel* (an acronym for *so*und *f*ixing *a*nd *r*anging), or *deep sound channel*, sound is efficiently trapped and transmitted long distances. For instance, certain whales may use the SOFAR channel to send sounds across entire ocean basins.

The idea of sending sounds through the SOFAR channel in an effort to detect the amount of ocean warming as a result of the greenhouse effect was initiated by Walter Munk of the Scripps Institute of Oceanography (Figure 16A, *upper inset*). His experiment, named **Acoustic Thermometry of Ocean Climate (ATOC)**, is designed to accurately measure the travel time of similar low-frequency sound signals through the SOFAR channel now and in the future. The speed of sound in seawater increases as temperature increases, so sound should take less time to travel the same distance in the future if, in fact, the oceans are warming.

In 1991, Munk's group successfully tested ATOC at Heard Island in the southern Indian Ocean, from which sound can reach many different receiving sites along straight-line paths (Figure 16A). The researchers deployed an underwater array similar to a series of loudspeakers that sent *acoustical* (*akouein* = to hear) signals for six days. These signals refracted into the ocean's SOFAR channel and were transmitted throughout the oceans. After traveling for many hours and as far as 19,000 kilometers (11,800 miles), the signals were received at shipboard recording stations.

The success of ship-based testing at Heard Island led to the establishment of a fixed sound source near Pioneer Seamount off California and an array of fixed receivers throughout the Pacific Ocean. In 1995, ATOC sound signals were sent again. Even though many precautions were taken to avoid any unwanted effects on marine mammals, three humpback whales were found dead in the area a few days after the sound transmissions had begun. The sounds were halted while the U.S. National Marine Fisheries Service (NMFS) conducted research to determine whether the sounds affected the hearing of nearby whales and contributed to their deaths. After extensive scientific study, their results indicated that marine mammals are unaffected by the transmissions and that the dead whales were an unfortunate coincidence. The long-term effect of ATOC signals on marine mammals—including marine mammal communication through the SOFAR channel—is poorly understood but is also likely to be minimal. The NMFS approved the project and transmissions from offshore California and Hawaii have been conducted without incident, producing a wealth of data that indicates a warming trend in the Pacific and establishing an important baseline for comparison with future measurements.



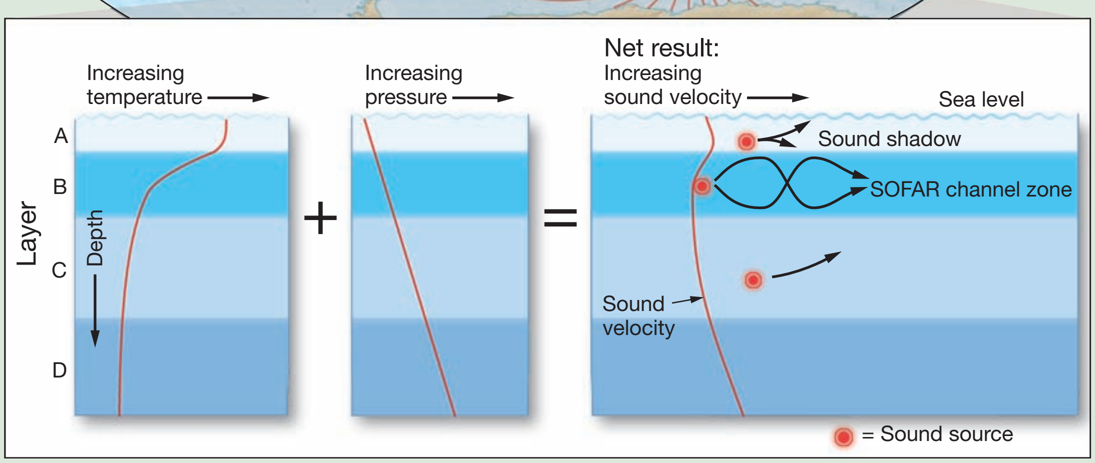


FIGURE 16A The ATOC experiment. Map showing Heard Island sound travel paths, photograph of oceanographer Walter Munk (*upper inset*), and diagram of the SOFAR channel (*lower inset*). Temperature and pressure conditions in the ocean combine to produce the SOFAR channel (*layer B*), which traps and transmits sound energy. Sound waves created in layers A and C are bent into the SOFAR channel and remain within it, allowing the sound to be transmitted across entire ocean basins.

The impacts of a warmer ocean are far-reaching and will persist for several centuries. For example, increased seawater temperatures are likely to affect temperature-sensitive organisms such as corals. As discussed in Chapter 15, warmer sea surface temperatures have been implicated in widespread coral bleaching events (see Box 15.1). In addition, increased seawater temperatures are likely to affect the distribution of sea ice, the ocean's deep-water circulation pattern, El Niño/La Niña events, and the development of hurricanes.

Increasing Hurricane Activity

Many scientists have suggested that warmer oceans would most certainly cause an increase in the general level of storminess because additional heat accelerates evaporation, which fuels hurricanes. In fact, the frequency and severity of recent hurricanes—especially those in the Atlantic Ocean (see Box 6.2)—have kindled a debate on the effect that global warming may have on the formation of hurricanes. Although the recent landfall of several large Atlantic hurricanes leads to a general impression that hurricanes have increased, there have been conflicting reports on the topic in the scientific literature. Some articles have attributed increases in hurricane intensity, numbers, and wind speeds to warmer sea surface temperatures, while others have claimed that changes in data-gathering methods and instrumentation are responsible for the trends. Other studies suggest that the apparent increase in hurricanes can be considered within the statistical limits of normal.

Although the number of tropical storms has not increased worldwide, the scientific consensus is that global warming has led to more intense hurricanes. In the most comprehensive study of recent hurricane activity to date, researchers demonstrate that there have been significant increases in tropical storm intensity and duration around the world since 1970 and that these trends are strongly related to rising sea surface temperatures. Another study of historical Atlantic hurricanes over the past 1500 years suggests that times of peak hurricane activity are related to increased sea surface temperatures and the reinforcing effects of La Niña–like climate conditions. Other research explicitly shows that the most energetic storm levels—those with Category 4 and 5 designations—have increased significantly, particularly in the North Atlantic and northern Indian Oceans. And, experts warn that as climate continues to warm as expected, there will likely be additional increases in peak hurricane wind speed and rainfall.

Changes in Deep-Water Circulation

Evidence from deep-sea sediments and computer models indicates that changes in the global deep-water circulation pattern can dramatically and abruptly affect climate. Circulation in the North Atlantic Ocean, which provides an important source of deep water (Figure 16.14), is particularly sensitive to these changes.

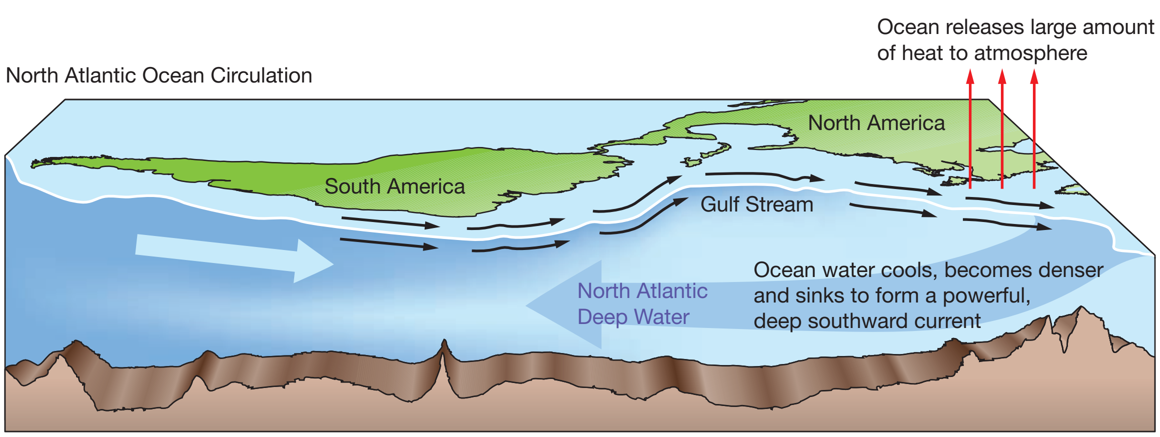


FIGURE 16.14 North Atlantic Ocean circulation. Perspective view of circulation in the North Atlantic Ocean, showing that the Gulf Stream carries a tremendous amount of heat northward that warms the North Atlantic region. As this water cools, it generates a huge volume of cold, salty, dense water called North Atlantic Deep Water that sinks into the deep-ocean basin and flows southward. Disruption of this circulation pattern could have severe effects on global climate.

STUDENTS SOMETIMES ASK . . .

The movie The Day After Tomorrow *depicts rapid climate change as a result of alterations in deep-water circulation. Could this really happen?*

Although Hollywood movies are well known for dramatization, what is interesting about this blockbuster 2004 film is that its story line is based on recent scientific findings: The ocean's deep-water circulation helps drive ocean currents around the globe and is important to world climate. In fact, strong evidence suggests that the North Atlantic deep-water circulation has already weakened and may further weaken during this century, resulting in unpleasant effects on our climate—but certainly not as rapid or as cataclysmic as the situation portrayed in the film. Computer models suggest that the continued weakening of the North Atlantic deep-water circulation will result in some long-term cooling, particularly over parts of northern Europe.

What drives deep-water circulation is the sinking of cold, dense surface waters at high latitudes, particularly in the North Atlantic. If surface waters stopped sinking because they are too warm and thus low in density, then the oceans would absorb and redistribute heat from solar radiation much less efficiently. This would likely cause even warmer surface water temperatures and much higher land temperatures than are experienced now.

Many scientific studies suggest that the buildup of greenhouse gases in the atmosphere will change ocean circulation. One way in which this could happen is that warmer air temperatures will increase the rate at which glaciers in Greenland melt, forming a pool of fresh, low-density surface water in the North Atlantic Ocean. This freshwater could inhibit the downwelling that generates North Atlantic Deep Water, reorganizing global circulation patterns and causing a corresponding change in climate. Many climate experts warn that a large outflow of freshwater from Greenland could take the North Atlantic system of currents to a tipping point, causing rapid reorganization of deep-water currents and related changes in climate. Indeed, evidence suggests that an outburst from a North American ice-dammed lake flooded the North Atlantic with freshwater about 8000 years ago, causing rapid global climate change. This event may be the type of scenario that the North Atlantic could experience again because of increased precipitation and melting of ice.

Melting of Polar Ice

Computer models have predicted that global warming will affect Earth's polar regions in a very dramatic way. One fundamental difference between the two polar regions is that in the Northern Hemisphere, the polar region is dominated by the Arctic Ocean and its cover of drifting sea ice (an ocean surrounded by land), whereas the South Pole is dominated by the continent of Antarctica and its thick ice cap, including shelf ice that extends into the ocean (land surrounded by an ocean).

FIGURE 16.15 Arctic sea ice decline. Perspective view of satellite data, showing the extent of Arctic sea ice in September 2007 compared with the average extent of sea ice from 1979–2000 (*red line*). Note the opening of an ice-free Northwest Passage. The substantial decrease in amount and thickness of Arctic Ocean sea ice is due to human-induced warming of the Arctic.

The Arctic is one of the locations where the effects of global warming are being most keenly felt (see Figure 16.13) and likely will experience quite dramatic changes in the future; this phenomenon is called *Arctic amplification*. Since 1978, satellite analysis of the extent of Arctic Ocean sea ice indicates that it is dramatically shrinking and thinning at an accelerating rate (Figure 16.15). In the past decade alone, there has been a loss of over 2 million square kilometers (800,000 square miles) of Arctic sea ice. In fact, measurements of the ice cap in 2007 revealed that it had shrunk to its smallest size since researchers began keeping records; its extent fell below the previous record low in 2005 by an area roughly the size of Texas and California combined. In addition, the interior ice is now unusually thin and spread out, which has resulted in wide patches of ice-free ocean during the summer—even at the North Pole.

Climate models are in general agreement that one of the strongest signals of greenhouse warming will be a loss of Arctic sea ice. Indeed, during the past 15 years, the decline in Arctic sea ice has occurred much faster than models had predicted. Cycles of natural variability are known to play a role in Arctic sea ice extent, but the sharp decline observed in the past two decades cannot be explained by natural variability alone. The accelerated Arctic sea ice melting appears to be linked to shifts in Northern Hemisphere atmospheric circulation patterns that have caused the region to experience unusually rapid warming. As a result, ocean temperatures in the Arctic Ocean have also increased, causing sea ice to melt from below. Disappearance of sea ice is likely to enhance future warming in the region because lower amounts of sea ice will reflect less of the Sun's radiation back into space, creating a positive-feedback loop and exacerbating the problem as heat is absorbed by the newly uncovered ocean. Researchers fear that the Arctic may be on the verge of a fundamental transition or "tipping point" that will lead to the Arctic having only seasonal ice cover. Some models, for example, suggest that the Arctic could experience the complete disappearance of summer sea ice as early as 2030.

The decrease of sea ice in the Arctic has already had profound effects on Arctic ecosystems. Polar bears (*Ursus maritimus*; Figure 16.16), for example, are excellent swimmers but do not hunt in the water. Instead, they require a platform of floating sea ice to capture their prey items, which are mainly seals. As the Arctic Ocean becomes more ice-free and the ice habitat shrinks, polar bears will have more difficulty finding adequate food and making dens. As a result, polar bear breeding and survival rates may decline below the point needed to maintain the population. Their habitat destruction has been so severe that polar bears were listed as Threatened Species in 2008, according to the U.S. Endangered Species Act. Studies reveal that polar bears are likely to lose nearly half of their summer sea ice habitat by mid-century, which would in turn reduce the world's polar bear population—currently estimated at 25,000—by two-thirds.

FIGURE 16.16 Habitat destruction threatens polar bears. Polar bears (*Ursus maritimus*) are reliant on floating sea ice as a feeding platform and for building dens. As a result of habitat destruction caused by shrinking Arctic sea ice, polar bears were designated a Threatened Species in 2008.

In addition, human inhabitants of the Arctic are also being affected by the lack of sea ice, as some of their food sources become scarcer because marine species have migrated further from shore to be near the ice edge. Arctic residents have complained that their weather is changing, and a recent study supports their claim. The study determined that the years with the least amount of Arctic sea ice had significantly stronger Arctic storms. One new opportunity that now exists, however, involves the creation of a new "Northwest Passage" shipping lane linking the North Pacific and North Atlantic Oceans through the largely ice-free portions of the Arctic Ocean (Figure 16.15).

While all these changes are taking place in the Arctic, different but equally dramatic ones are taking place in Antarctica, particularly in the western part of Antarctica that includes the Antarctic Peninsula. As discussed in Chapter 6, Antarctica produces many icebergs from glaciers on land. The rate at which Antarctica is producing icebergs—especially large icebergs—has increased in recent years. For example, the Antarctic Peninsula's Larsen Ice Shelf has decreased by more than 40% over the past decade, including a huge release of 3250 square kilometers (1250 square miles) of ice during two months in 2002 (see Figure 6.24d). In 2006, Antarctica lost nearly 200 billion metric tons (220 short tons) of ice; during 10 days in 2008, the Wilkins Ice Shelf lost over 400 square kilometers (160 square miles) of ice. The rate of thinning of the Pine Island Glacier—the largest stream of fast-moving ice on the West Antarctic Ice Sheet—quadrupled from 1995 to 2006. And, in the past 30 years, there have been 10 major Antarctic ice shelf collapses—including the disappearance of the ice shelves knows as Jones, Larsen A, Muller, and Wordie—after some 400 years of relative stability. Scientists attribute this catastrophic retreat to warming in Antarctica; the Antarctic Peninsula has experienced some of the greatest amount of warming worldwide (see Figure 16.13). In fact, Antarctica has warmed at a rate of about 0.12°C (0.22°F) per decade since 1957, for a total average temperature rise of 0.5°C (1°F) (Figure 16.17).

Recent Increase in Ocean Acidity

The human-induced increase in the amount of carbon dioxide in the atmosphere has some severe implications for ocean chemistry and for marine life. Recent studies show that a little less than half of the carbon dioxide released by the burning of fossil fuels stays in the atmosphere and about a third currently ends up in

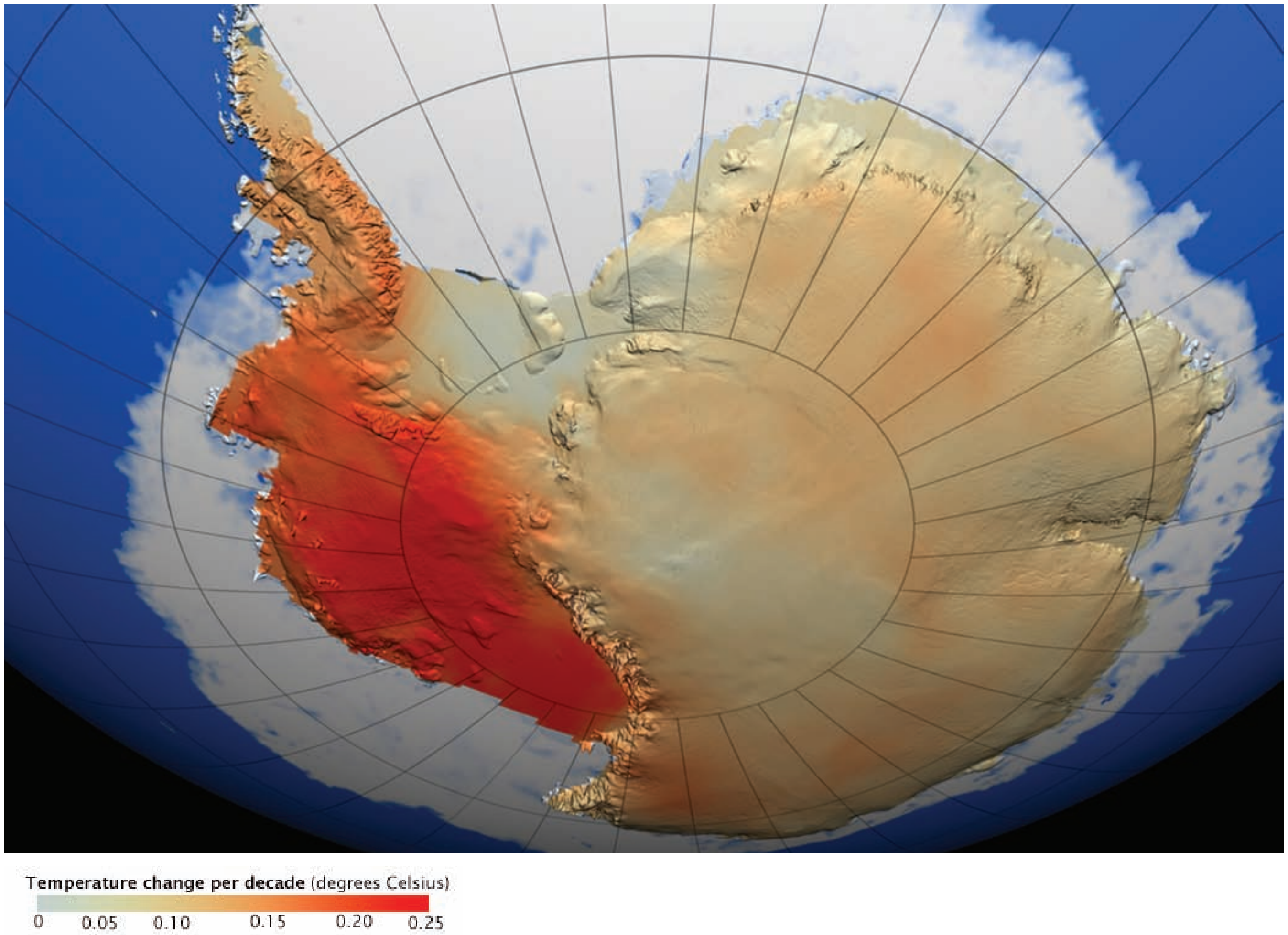


FIGURE 16.17 Antarctic warming trends. This satellite image shows the amount of warming that Antarctica has experienced since 1957. The data are from satellites and weather station measurements. Notice that western Antarctica has experienced the greatest temperature change.

the oceans, dissolving into seawater at the ocean surface. Evidence is mounting that this additional carbon dioxide overwhelms the ocean's natural ability to buffer itself.[6] The absorbed carbon dioxide forms carbonic acid in seawater, lowering the ocean's pH (increasing its acidity in a process called **ocean acidification**) and changing the balance of carbonate and bicarbonate ions. In fact, the oceans have already absorbed enough carbon dioxide for surface waters to have experienced a pH decrease of 0.1 pH unit since preindustrial times; a recent study has confirmed a 0.04 pH unit decrease in the North Pacific Ocean during just the past two decades. Other studies suggest an additional pH decrease will be likely in the future.

Moreover, this shift toward increased acidity and the changes in ocean chemistry that ensue makes it more difficult for certain marine creatures to build and maintain hard parts out of easily dissolved calcium carbonate. The decline in pH thus threatens a diverse assortment of calcifying organisms—creatures that grow calcium carbonate skeletons or shells—such as coccolithophores, foraminifers, pteropods, calcareous algae, sea urchins, mollusks, and corals (Figure 16.18). These organisms provide essential food and habitat to many other species, so their demise could affect entire ocean ecosystems. Recent studies have shown that in the past 20 years, ocean acidification has already caused a 15% decrease in the growth rate of corals in Australia's Great Barrier Reef.

The graph in Figure 16.19 shows the projected increase of carbon dioxide in the ocean and the resulting decrease in ocean pH (rise in acidity). The graph shows that if the current trend of human-induced carbon dioxide emissions

[6]For a discussion of the ocean's buffering system and pH, see Chapter 5.

(a) Coccolithophores (diameter of each = 20 microns, or 0.0008 in.)

(b) Pteropod (diameter = 2 mm, or 0.08 in.)

(c) Sea urchins

(d) Corals

FIGURE 16.18 Examples of marine organisms that are affected by increased ocean acidity. Organisms that make their skeletons or shells out of easily dissolved calcium carbonate include **(a)** coccolithophores, which are type of phytoplankton; **(b)** a pteropod, which is a zooplankton that is a small swimming snail with a shell; **(c)** sea urchins; and **(d)** corals. As ocean acidity increases, these and many other types of organisms will have a more difficult time building and maintaining hard parts.

continues, by 2100 the ocean will experience a pH decrease of at least 0.3 pH unit; some studies indicate that pH could decrease by as much as 0.5 pH unit. Even at the lower value, this reduction of pH represents a change in ocean chemistry that has not occurred for millions of years. An additional concern is that this increase in acidity will eventually be transmitted to the deep-ocean floor by the initiation of deep currents from cold, dense surface waters. This is particularly worrisome because the organisms that inhabit deep-ocean habitats are adapted to its stable, unchanging environment.

Several factors influence the amount of carbon dioxide absorbed by the oceans. Processes involved in distributing carbon dioxide within the ocean–atmosphere system cause it to be divided unequally between the two reservoirs. For example, carbon dioxide gas is readily absorbed by the ocean and, as a result, the ocean contains a much larger amount of carbon dioxide than the atmosphere.[7] The amount of

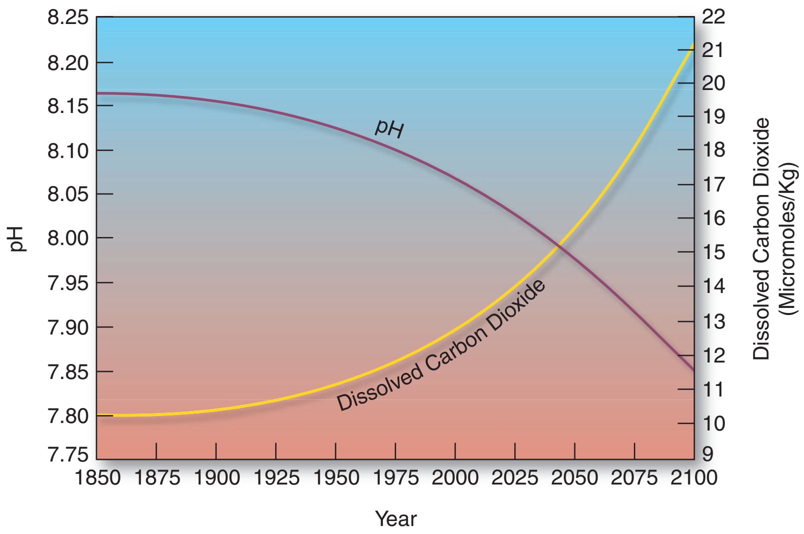


FIGURE 16.19 Historical and projected dissolved carbon dioxide and ocean pH. As the concentration of carbon dioxide in the ocean increases, so does ocean acidity (causing pH to decline).

[7]Of the three places where carbon dioxide resides—atmosphere, ocean, and land biosphere—approximately 93% is found in the ocean. The atmosphere, in contrast, contains the smallest amount.

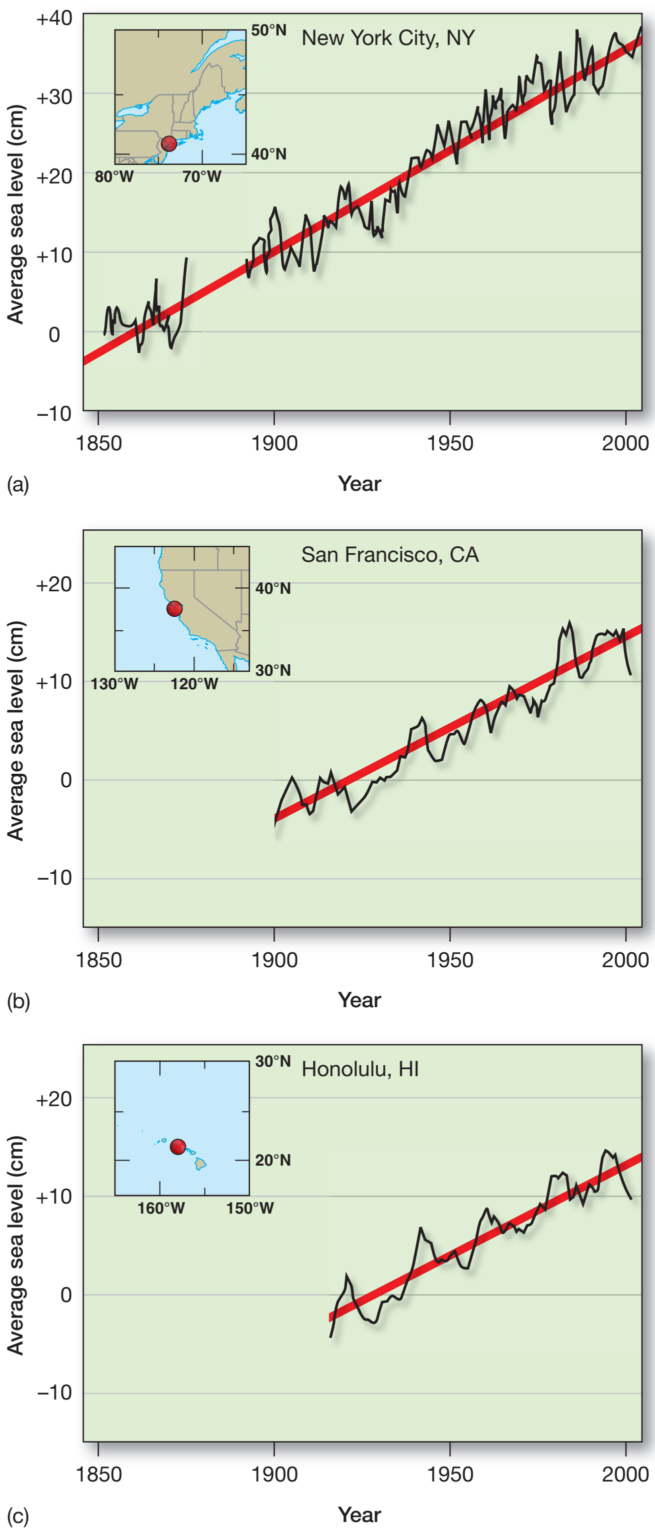


FIGURE 16.20 Measured relative sea level rise from tide gauges. Sea level data from **(a)** New York City, New York, shows an increase of 40 centimeters (16 inches) since 1850. Similar increases are shown in **(b)** San Francisco, California, and **(c)** Honolulu, Hawaii. While some of the documented rise is due to local effects (for example, New York is experiencing isostatic uplift after glaciation), the majority is likely caused by the addition of water from the melting of continental ice caps and glaciers as well as from thermal expansion of warmer ocean water.

carbon dioxide dissolved in the ocean varies with the chemistry of seawater but also has certain limits. Once the ocean approaches saturation of carbon dioxide, it will absorb less of the gas, which means that more will remain in the atmosphere. As the ocean warms, it will further reduce the amount of carbon dioxide that goes into the oceans because warmer water can't hold as much dissolved gas. Another factor is how rapidly deep waters mix with surface waters: The more rapid the mixing, the more it facilitates the uptake of carbon dioxide from the atmosphere. If deep-water circulation slows as predicted, this will also slow the uptake of carbon dioxide from the atmosphere. In essence, more of the carbon dioxide being released now will stay in the atmosphere, where it will create additional human-caused warming.

Rising Sea Level

Analysis of worldwide tide records indicates that there has been a rise in global sea level of between 10 and 25 centimeters (4 and 10 inches) over the past 100 years. At certain tide-recording stations where data go back well into the 19th century, there has been an increase in relative sea level of as much as 40 centimeters (16 inches) over the past 150 years (Figure 16.20). More recently, satellite altimeter data since 1993 indicate a global increase in sea level of about 3 millimeters (0.1 inch) per year (Figure 16.21).

Clearly, sea level is rising. Two main factors contribute to this global rise in sea level: (1) thermal expansion of ocean water as it warms and (2) an increase in the amount of water in the ocean from the melting of ice on land. Note that melting of floating sea ice (such as in the Arctic Ocean) or floating ice shelves (such as those that fringe Antarctica) does not contribute to sea level rise because that ice/water is already in the ocean. More specifically, in order of their overall contribution to the observed global rise in sea level (Figure 16.22), the main contributors are:

1. The melting of Antarctic and Greenland ice sheets
2. The thermal expansion of ocean surface waters
3. The melting of land glaciers and small ice caps
4. The thermal expansion of deep-ocean waters

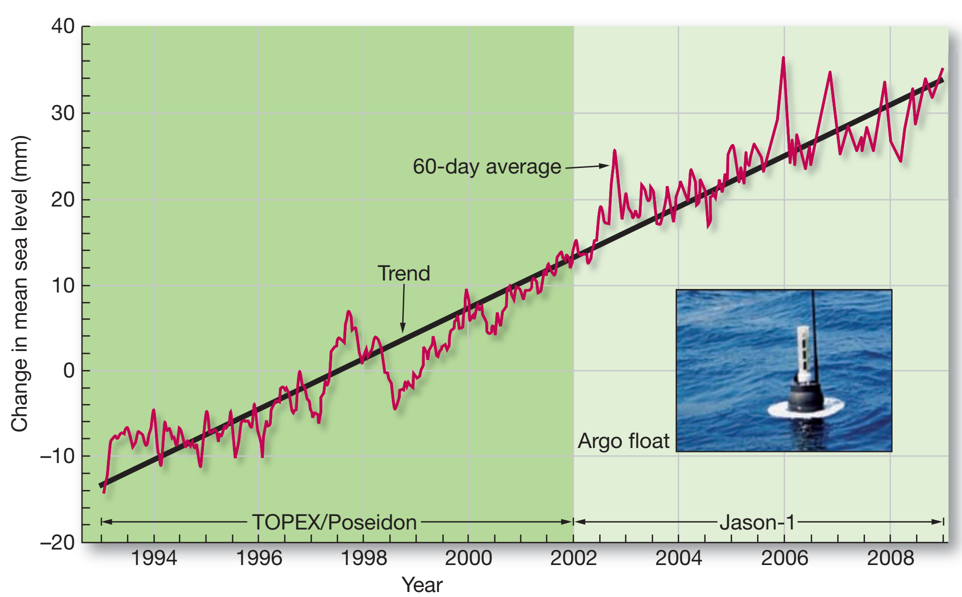


FIGURE 16.21 Sea level rise determined by satellites. Radar altimeter data from TOPEX/Poseidon and Jason-1 satellites combined with Argo drifting floats (*inset*; see also Chapter 7) reveal that sea level rose 3 millimeters (0.1 inch) per year since 1993. Researchers attribute about half of that increase to melting ice and the other half to thermal expansion as the ocean absorbs excess heat from the atmosphere.

An additional factor that affects global sea level is the storage of water on land in reservoirs. A recent study indicates that the amount of this storage has varied but generally increased since 1900 and suggests that without reservoirs, sea level would have risen even more.

Although the current rate of sea level rise might seem inconsequential, even a small amount of sea level rise can severely affect regions that have a gently sloping shoreline, such as the U.S. Atlantic and Gulf Coasts. Hazards associated with sea level rise include drowning of beaches, accelerated coastal erosion, permanent inland flooding, alteration of coastal ecosystems, loss of protective coastal wetlands, and increased damage from destructive storms. Moreover, if global warming increases the intensity of hurricanes, as discussed above, damage to coastal regions will be even greater.

The current rate of global sea level rise, though small, is likely to increase as Greenland and Antarctic ice sheets experience additional warming and make a greater contribution to sea level rise. In fact, detailed studies of Antarctic ice thickness reveal that the rate at which the ice is thinning near the coast has doubled since the 1990s. Neither the Greenland or Antarctic ice sheets are likely to disappear before 2100, but there is the danger that global warming could trigger massive and catastrophic discharges of ice from these ice sheets. A recent study determined that if the West Antarctic Ice Sheet were to collapse, it would raise global sea level by about 3.2 meters (10.5 feet).

According to recent models, the rate of sea level rise will increase with increased global warming. Studies of sea level rise that include both thermal expansion and ice-sheet contributions project a rise in sea level by 2100 of between 0.5 and 1.4 meters (1.6 and 4.6 feet), which is particularly worrisome for low-lying coastal regions. In addition, increased amounts of human settlement and development in coastal regions compound the problem. And, projections suggest that sea level may well rise by several meters in the next few hundred years.

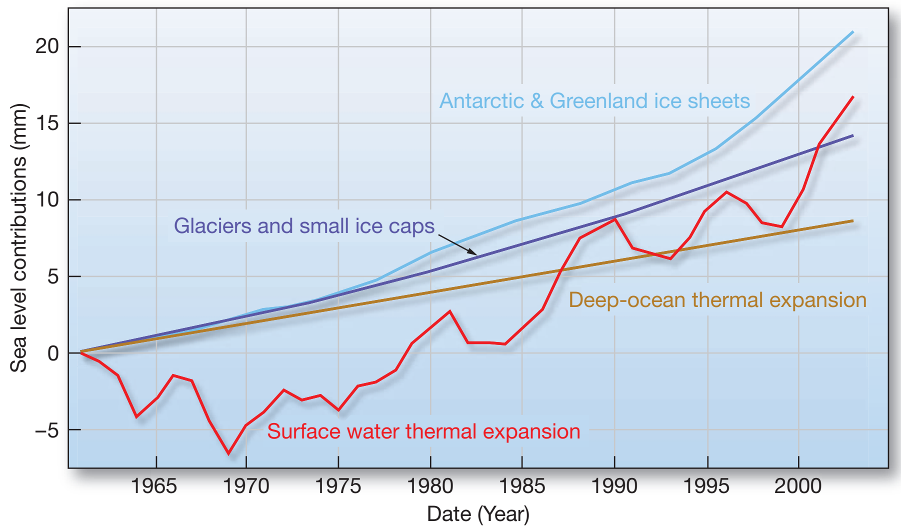


FIGURE 16.22 Main components that contribute to global sea level rise. Each line on this graph shows how much each of the four main components contributes to overall sea level rise. The four components are (1) Antarctic and Greenland ice sheets, (2) glaciers and small ice caps, (3) deep-ocean thermal expansion, and (4) surface water thermal expansion.

Other Predicted Changes

Several other ocean changes are predicted to result from global warming. One is the transmission of sound in the sea (see Box 16.1). A recent study indicates that the increasing amount of carbon dioxide dissolved in seawater makes it more efficient at transmitting sound waves. Researchers predict that by 2050, ocean sounds such as whale calls may travel 70% farther than today; the effect on marine animals is unknown.

Another ocean effect is lower dissolved oxygen in seawater. As discussed in Chapter 12, dissolved oxygen in seawater is vital for most marine animals, which extract dissolved oxygen directly from seawater. As the ocean warms, its ability to hold and carry dissolved oxygen is diminished, while at the same time the metabolic rate of marine organisms increases, which means they need higher levels of dissolved oxygen. In addition, warmer surface waters will limit the overturning process that brings oxygen to deep waters. At current rates of carbon dioxide emissions, studies predict severe oxygen-depleted zones both at the surface and into deeper waters for thousands of years. Reduced oxygen levels will likely have dramatic consequences for marine ecosystems and coastal regions that already experience oxygen-depleted "dead" zones (see Box 13.2).

Still another effect of ocean warming is the alteration of oceanic productivity, which has implications for the distribution of essentially all marine organisms. As ocean surface waters warm, ocean stratification will increase and a stronger

thermocline will develop.[8] As a result, productivity is expected to decrease because of fewer nutrients caused by diminished upwelling and by upwelling bringing more nutrient-depleted warmer waters to the surface. Recall from Chapter 13 that **phytoplankton** (*phyto* = plant, *planktos* = wandering)—which include marine algae such as *diatoms* and *coccolithophores*—comprise the base of most marine food webs and thus support the rest of the larger organisms in the oceans.

Warmer waters can also affect marine organisms directly. Many types of phytoplankton and other organisms are very sensitive to changes in water temperature. For example, a large study of phytoplankton in the North Atlantic shows that ocean warming has increased the abundance of phytoplankton in cooler regions and decreased them in warmer waters. A recent study off California documents a decrease in cool-water organisms caused by a deep, penetrative warming not observed in the past 1400 years. In these organisms' place, there has been a boost in the population of 25 fish groups that prefer warmer waters as surface waters have shifted from cold to warm temperatures over recent decades.

In response to rising ocean temperatures, marine organisms have also begun to migrate into deeper waters and toward the poles. As verification of this trend, a recent study of fish species in the North Sea suggests that many commercially important fish, such as cod, whiting, and anglerfish, have shifted northward as much as 800 kilometers (500 miles). The report notes that if these climate trends continue, some species of fish may withdraw completely from the North Sea by 2050. Changes such as these have severe implications for the health of marine ecosystems and the sustainability of marine fisheries.

Finally, there is great concern amongst the scientific community that the human-induced greenhouse effect may bring unpleasant surprises such as abrupt changes in Earth systems that could not have been predicted.

KEY CONCEPT

Changes occurring in the ocean due to increased global warming include increased ocean temperatures, more intense hurricane activity, changes in deep-water circulation, melting of polar ice, increased ocean acidity, and rising sea level.

16.5 What Should Be Done to Reduce Greenhouse Gases?

The consensus of scientific studies suggest that the planet has warmed due to human-caused greenhouse gas emissions. Moreover, scenarios for future warming look bleak. For example, if human-caused emissions remain at or near their current rate of increase, atmospheric carbon dioxide is expected to exceed 500 parts per million sometime between 2050 and 2100, causing global temperatures to increase by at least 2°C (3.6°F) and more likely by about 5°C (9°F). Based on paleoclimate data, these values of atmospheric carbon dioxide and global temperature significantly exceed those of at least the past 420,000 years.

Recently, there have been serious discussions about deliberately manipulating Earth's climate system to counteract human-caused global warming and its unwanted effects. These manipulations—called **global engineering**, or *geoengineering*—are very controversial. Some of the concerns about any type of global engineering include the justification for intentionally altering any of Earth's systems on a global scale, the possibility of harmful side effects, who should pay for its implementation, and whether it would have to be constantly maintained. In addition, skeptics of global engineering point out that it distracts from perhaps the most immediate way of limiting human-caused climate change: reducing the amount of greenhouse gases that are spewed into the atmosphere.

Most global engineering proposals fall into two general types: (1) reducing the amount of sunlight reaching Earth or (2) removing human-caused greenhouse gases from the atmosphere and disposing of them somewhere else. Examples of the first type include spraying sulfate aerosols into the atmosphere

[8]For more details on the thermocline (layer of rapidly changing temperature), see Chapter 5.

to mimic the cooling effect of a major volcanic eruption or installing thousands of reflective sunshades in orbit to block incoming sunlight. Examples of the second type include removing atmospheric carbon dioxide and placing it into subsurface layers within Earth or into the deep ocean.

In this section, we'll examine how the oceans naturally counteract global warming, how the ocean system reduces greenhouse gases, and what potential solutions exist.

The Ocean's Role in Reducing Global Warming

Because the oceans naturally absorb vast amounts of carbon dioxide from the atmosphere, the oceans therefore play a vital role in reducing the greenhouse effect. In fact, the vast majority of carbon dioxide in the ocean–atmosphere system is found in the ocean because carbon dioxide is approximately 30 times more soluble in water than are other common gases. Currently, a little less than half of the carbon dioxide humankind releases into the atmosphere stays there; about a third enters the oceans with the rest absorbed by land plants.

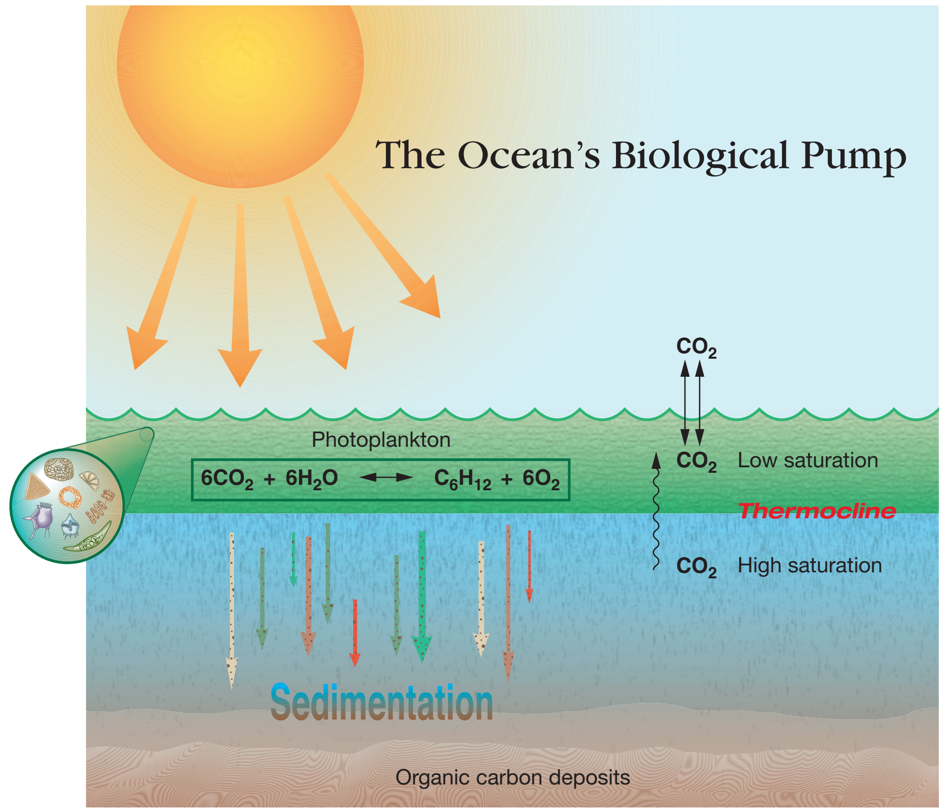


FIGURE 16.23 The ocean's biological pump. Schematic view of the ocean's biological pump, which removes carbon dioxide from the atmosphere.

THE OCEAN'S BIOLOGICAL PUMP What happens to the carbon dioxide that enters the ocean? Most of it is incorporated into organisms through photosynthesis and through their secretion of carbonate shells. Moreover, carbon dioxide is cycled very effectively from the atmosphere to the ocean. In fact, more than 99% of the carbon dioxide added to the atmosphere in the geologic past by volcanic activity has been removed by the ocean and deposited in marine sediments as biogenous calcium carbonate and fossil fuels. Thus, the ocean acts as a *repository* (or *sink*) for carbon dioxide, soaking it up and removing it from the environment as sea floor deposits. This process of removing material from sunlit surface waters to the sea floor is called a **biological pump** because it "pumps" carbon dioxide and nutrients from the upper ocean and concentrates them in deep-sea waters and sea floor sediments (Figure 16.23).

KEY CONCEPT

The ocean plays a key role in reducing atmospheric greenhouse gases through its biological pump; it also minimizes global warming by acting as a thermal sponge.

THE OCEAN AS A THERMAL SPONGE Due to its unique thermal properties,[9] water can absorb large quantities of heat without much change in temperature. Thus, the thermal properties of the ocean make it ideal for minimizing the increase in global temperature. Further, the oceans serve as the planet's biggest single reservoir for surplus energy. If not for the oceans, the planet would be experiencing a much greater increase in temperature. In essence, the oceans act as a "thermal sponge," absorbing heat but not increasing much in temperature and so minimize the amount of warming experienced. Even so, recent studies have documented that the heat content of the oceans has been increasing (Figure 16.24).

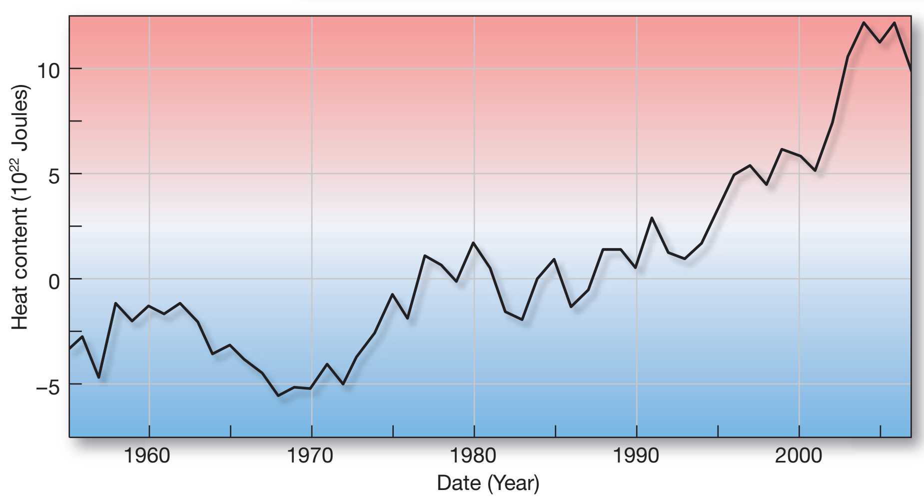


FIGURE 16.24 Heat content of the oceans. Graph showing how the heat content of the oceans has increased since the 1950s. The short-term variability of the curve shows the natural variation of the ocean's heat content and is influenced by factors such as El Niño/La Niña events.

[9]For a discussion of water's unique thermal properties, such as latent heat, see Chapter 5.

Possibilities for Reducing Greenhouse Gases

There is much debate about what to do about the increasing human-caused emissions in the atmosphere. One idea is to eliminate human emissions before they even get into the atmosphere. Other proposals involve using the oceans to reduce the amount of human-caused emissions in the atmosphere. Let's examine two of these proposals.

THE IRON HYPOTHESIS Stimulating productivity in the ocean has been proven to remove carbon dioxide from the atmosphere. Through photosynthesis, phytoplankton such as diatoms convert carbon dioxide dissolved in the ocean to carbohydrate and oxygen gas. By capturing and removing additional amounts of carbon dioxide from the ocean, the ocean can, in turn, absorb more heat-trapping carbon dioxide from the atmosphere, thus cooling the planet.

Areas of the ocean that have relatively low productivity, such as in the tropics, are a good place to stimulate productivity and thus increase the amount of carbon dioxide removed from the atmosphere. In 1987, oceanographer John Martin determined that the absence of the essential nutrient iron limited productivity in tropical oceans, so he proposed fertilizing the ocean with iron to increase its productivity. "Give me a half a tanker of iron and I'll give you the next ice age," Martin once famously quipped. Subsequently, this idea became known as the **iron hypothesis** (Figure 16.25). In 1993, Martin's associates tested the idea by adding a soluble solution of finely ground iron to a small patch of ocean near the Galápagos Islands in the Pacific Ocean. Their results, combined with the results of about a dozen other open-ocean experiments worldwide since 1993, confirmed that adding iron to the ocean increased phytoplankton productivity up to 30 times. In fact, some of the patches of iron-enriched high productivity were visible to Earth-orbiting satellites.

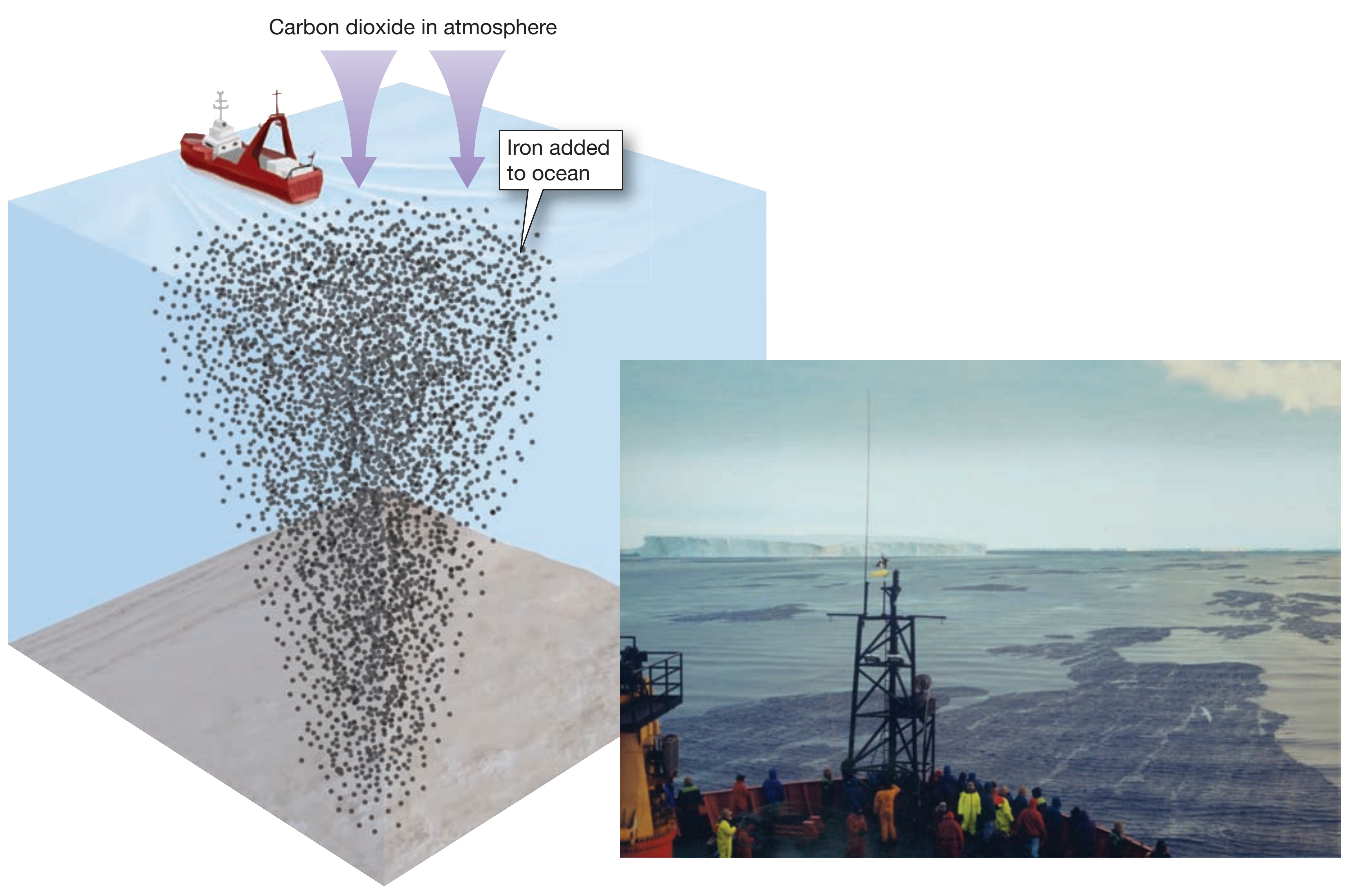


FIGURE 16.25 The iron hypothesis. Seeding the ocean with the essential nutrient iron stimulates productivity and draws in heat-trapping carbon dioxide from the atmosphere that is used by phytoplankton. Some of this carbon dioxide, tied up as tissue or in fecal pellets, sinks toward the sea floor, thereby removing it from the environment. Photo (*inset*) shows a view from a research vessel involved in applying finely-ground iron to the ocean near Antarctica.

Although the results from these small-scale open-ocean experiments proved that the iron hypothesis did indeed draw carbon dioxide out of the atmosphere, the scientists had to overcome problems grinding the iron fine enough, dispersing the iron, and keeping it in solution for long periods of time. A more serious problem, however, is the long-term global environmental effects of increasing the amount of carbon dioxide in the ocean and stimulating biological productivity. For example, there is concern that severe oxygen depletion of seawater could occur in areas where iron fertilization is conducted because the large population of algae that is produced eventually dies and decomposes, thus consuming dissolved oxygen. In addition, decomposition releases byproducts such as carbon dioxide and nitrous oxide—both important greenhouse gases. As discussed previously, higher amounts of carbon dioxide in the ocean lead to increased ocean acidity, which is a problem for marine life and marine ecosystems. Another problem is from interference with the natural ecology of large oceanic regions—and its unforeseeable consequences. Nevertheless, even larger open-ocean experiments have been proposed and several private companies have filed patents for ocean-fertilization technologies to enable ocean fertilization to occur on a commercial scale.

SEQUESTERING EXCESS CARBON DIOXIDE IN THE OCEANS Successful experiments have involved capturing emissions either before they are released into the atmosphere or directly from the atmosphere and then pumping the gas into the deep ocean or underground reservoirs. This process—called **sequestering** (*sequester* = depository) carbon dioxide—thereby removes carbon dioxide from the atmosphere and, as a result, reduces global warming. If the deep ocean is used as a disposal site for carbon dioxide, however, there are concerns about how it would impact deep-sea chemistry and, as a result, marine ecosystems. In addition, it is unclear how long the sequestered carbon dioxide will stay in the deep ocean because of deep-water circulation patterns. However, the capture of carbon dioxide emissions and their subsequent disposal into deep reservoirs beneath the sea floor is already occurring at a handful of test sites worldwide.

The Kyoto Protocol: Limiting Greenhouse Gas Emissions

The mounting scientific evidence that global warming and some of its side effects are occurring has led to international efforts to address the human contribution to the greenhouse effect. A number of international conferences have resulted in an agreement among 60 nations to voluntarily limit greenhouse gas emissions. This agreement, which is called the **Kyoto Protocol** (because it was created at an international conference held in 1997 in Kyoto, Japan), sets target reductions for each country. For example, industrialized countries (such as the United States, which constitutes only about 5% of world population but is responsible for about 20% of worldwide carbon dioxide emissions[10]) are to reduce their collective emission of six greenhouse gases by at least 5% by 2012 compared to 1990 levels. Although 122 nations (representing 44% of the total worldwide carbon dioxide emissions) have ratified the treaty, the U.S. government has withdrawn its support for the protocol, citing potential harm to the world economy.

In late 2009, an international agreement reached at a meeting of delegates from both industrialized nations and major emerging economies at the United Nations Climate Change Conference in Copenhagen, Denmark, formally recognized a mandate to curb human-induced greenhouse gas emissions. The accord cites a goal of holding the global rise in average global temperatures to 2ºC (3.6ºF) but does not specify a long-term method for reducing emissions.

[10]China, which is a highly populated and rapidly industrializing country, recently surpassed the United States as the leading carbon dioxide emitter worldwide. The United States is currently second, with India and Russia next.

STUDENTS SOMETIMES ASK . . .

What can I do to help with the problem of global warming?

Even though global warming is a worldwide problem, there are many things concerned individuals can do to help curb greenhouse gas emissions:

1. *Drive smart:* Tune up your car and drive with properly inflated tires.
2. *Write your politicians:* Urge them to raise fuel economy standards for vehicles.
3. *Go green:* Support clean, renewable, non-fossil-fuel energy sources.
4. *Switch lights:* Replace incandescent light bulbs with energy-efficient compact fluorescent bulbs.
5. *Check your house:* Insulate and weather-strip; ask your utility company for a free energy audit.
6. *Become a smart water consumer:* Turn your water heater down and use low-flow faucets.
7. *Buy energy-efficient electronics and appliances:* Replace older, inefficient refrigerators and air conditioners.
8. *Plant a tree, protect a forest:* Preserve plant communities, which absorb carbon dioxide.
9. *Reduce, reuse, and recycle:* Support recycling efforts by choosing recycled products.
10. *Educate and vote:* Educate others and support measures that encourage energy conservation.

Note that these measures are all sound practices for preserving the environment that make sense no matter what the future levels of global warming might be.

Even if greenhouse gas concentrations stabilized today, with no additional increases, the planet would continue to warm by about 0.6°C (1°F) over the next century because it takes years for Earth's climate system to fully react to increases in greenhouse gases. This future warming is often referred to as Earth's *commitment to warming*. Based on plausible emissions scenarios, the IPCC estimates that average surface temperatures could rise between 2°C and 6°C (3.6°F and 10.8°F) by the end of the 21st century. Scenarios that assume that people will burn even larger amounts of fossil fuels than we do today give warming estimates in the top end of this temperature range, while the scenarios that assume that greenhouse gas emissions will grow slowly or not increase at all suggest a much smaller amount of warming. Not since the end of the last ice age 10,000 years ago, when Earth warmed by about 5°C (9°F), has the average temperature changed as dramatically as the change that scientists are predicting in less than 100 years.

At this point, it is very clear that human activities—such as burning fossil fuels, releasing emissions, and land use changes—are altering the environment on a global scale. Although the changes cannot be completely eliminated, many human impacts can be reduced. For instance, activities that affect the environment most severely—such as the high rate of consumption of fossil fuels and their subsequent harmful emissions—need to be decreased. In addition, plant communities must be preserved and much of what has already been removed by deforestation must be replaced in order to halt further damage. Finally, a high priority must be placed on research that improves our understanding of how Earth's climate system works.

KEY CONCEPT

Possibilities for reducing greenhouse gases include adding iron to the ocean to stimulate productivity and absorbing carbon dioxide from the atmosphere; sequestering excess carbon dioxide in the deep ocean; and limiting greenhouse gas emissions.

Chapter in Review

- *Earth's climate system includes the atmosphere, hydrosphere, geosphere, biosphere, and cryosphere* (the ice and snow that exists at Earth's surface). This system involves *exchanges of energy and moisture* that occur among the five spheres. Both *positive-feedback loops* that reinforce changes and *negative-feedback loops* that counteract changes modify Earth's climate.

- *Paleoclimatology*, the study of Earth's past climate, uses *proxy data*, which consist of *natural recorders of past climate*, including *sea floor sediments*, *glacial ice*, *fossil pollen*, *tree-growth rings*, and information contained in *historical documents*.

- *Several explanations have been formulated to explain Earth's climate change.* Current hypotheses for *natural factors* (causes unrelated to human activities) of climate change include *changes in the Sun's output associated with sunspots, variations in Earth's orbit, volcanic activity, and movement of Earth's tectonic plates*. Although natural mechanisms have altered climate in the past, *recent climate change is greater than can be explained by any natural factors*.

- Assessment reports published by the *Intergovernmental Panel on Climate Change (IPCC)* clearly document that the *current climate changes observed on Earth are due primarily to human activities that release heat-trapping greenhouse gas emissions to the atmosphere*.

- *The increase in average worldwide temperature is called global warming*. Although the warming of Earth's surface and atmosphere is a natural process controlled by the *greenhouse effect*, it is also being *altered by human greenhouse gas emissions*, a phenomenon that is often referred to as the *enhanced greenhouse effect*.

- *The greenhouse effect is produced by incoming sunlight that changes in wavelength, thus heating Earth. Energy reaching Earth from the Sun is mostly in the ultraviolet and visible regions* of the electromagnetic spectrum, whereas *energy radiated back to space from Earth is primarily in the infrared (heat) region*. *Water vapor, carbon dioxide, methane*, and other trace gases absorb infrared radiation and thus heat the atmosphere.

- *Earth's average surface temperature has warmed over the past century* and there is strong evidence that it is due primarily to human-caused increases of certain *heat-trapping gases such as carbon dioxide and methane*. Models predict that there will be a *strong warming of high northern latitudes*, a moderate warming of middle latitudes, and relatively little warming in low latitudes. Other predicted changes caused by global warming include *changes in the length of seasons, more intense heat waves, changes in both average and extreme temperature and precipitation*, *retreat of mountain glaciers, alteration of the range of infectious diseases, and shifts in the distribution of plants and animals*.

- *Changes that have been observed in the oceans due to global warming include increased ocean temperatures, more intense hurricane activity, changes in deep-water circulation, melting of polar ice, increase in ocean acidity, and rising sea level.* These changes in the ocean *will continue for centuries*.

- *The ocean removes carbon dioxide from the atmosphere by its biological pump*, which pumps carbon dioxide into sea floor deposits. The ocean also acts as a *thermal sponge by soaking up excess heat from the atmosphere*, thereby minimizing the amount of warming experienced.

- *The ocean can be used as a repository for some of society's carbon dioxide emissions* through either the *iron hypothesis, which stimulates phytoplankton productivity with the addition of finely ground iron*, or through *sequestering excess carbon dioxide by pumping it directly into the deep ocean*. However, the *effect* that these proposals might cause in the ocean is largely *unknown*.

- *The Kyoto Protocol establishes limits on greenhouse gas emissions,* but the *United States has not agreed to support it* because of potential harm to the economy. Nevertheless, there is already a *commitment to warming* and various *scenarios can be used to predict the amount of future warming*.

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Key Terms

Acoustic Thermometry of Ocean Climate (ATOC) (p. 482)
Biological pump (p. 491)
Climate (p. 469)
Climate system (p. 469)
Feedback loop (p. 470)
Fossil fuel (p. 477)
Global engineering (p. 490)
Global warming (p. 475)
Greenhouse effect (p. 475)
Greenhouse gases (p. 477)
Heat budget (p. 476)
Intergovernmental Panel on Climate Change (IPCC) (p. 474)
Iron hypothesis (p. 492)
Kyoto Protocol (p. 493)
Ocean acidification (p. 486)
Paleoclimatology (p. 472)
Phytoplankton (p. 490)
Proxy (p. 471)
Sequester (p. 493)
Sunspots (p. 472)
Thermocline (p. 490)

Review Questions

1. List the five parts of Earth's climate system.

2. What are climate feedback loops? Give some examples of both types.

3. What are proxy data? List several examples. Why are such data necessary for paleoclimatology studies?

4. List several examples of natural climate change. Do natural climate change mechanisms account for the recent climate changes that Earth is experiencing?

5. Describe the fundamental difference between solar radiation absorbed at Earth's surface and the radiation that is primarily responsible for heating Earth's atmosphere.

6. Discuss the greenhouse gases in terms of their relative concentrations in the atmosphere and their relative contributions to global warming.

7. Why has the carbon dioxide level of the atmosphere been rising for more than 150 years?

8. How are atmospheric temperatures likely to change as carbon dioxide levels continue to increase?

9. Describe several changes that are already occurring in the oceans because of global warming.

10. What physical conditions produce a SOFAR channel, or sound channel, below the ocean's surface? How is the SOFAR channel being used to detect warming in the oceans?

11. How does the ocean's biological pump work to help reduce global warming?

12. How does the ocean act as a thermal sponge, thereby helping minimize the amount of global warming experienced?

13. What is the Kyoto Protocol? Why has the United States not agreed to support it?

14. What commitment to warming will Earth experience in the future? What strategies exist to reduce future warming?

Critical Thinking Exercises

1. What is the difference between weather and climate? If it rains in a particular area during a day, does that mean that the area has a wet climate? Explain.

2. Some friends tell you that they've heard that the recent climate change Earth is experiencing is just part of a natural cycle. What would you explain to them—including using any figures from this chapter—to help convince them otherwise?

3. Sketch a labeled diagram that shows how Earth's greenhouse effect works.

4. Describe the iron hypothesis, and discuss the relative merits and dangers of undertaking such a "global engineering" project that could cause dramatic changes in the environment worldwide.

Oceanography on the Web

Visit the *Essentials of Oceanography* Online Study Guide for Internet resources, including chapter-specific quizzes to test your understanding and Web links to further your exploration of the topics in this chapter.

The *Essentials of Oceanography* Online Study Guide is at http://www.mygeoscienceplace.com/.