8

Sustaining Our Atmosphere and Climate

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Learning Outcomes

After reading this chapter, you should be able to

- Differentiate between the troposphere and the stratosphere and between weather and climate.
- Describe different sources of air pollution and their environmental and health impacts.
- Identify different ways to reduce air pollution.
- Describe causes and impacts of stratospheric ozone depletion.
- Explain the relationship between the Earth's energy balance and the greenhouse effect.
- List evidence for the warming of the Earth and humanity's role in global climate change.
- Describe the impacts of global climate change on the environment, economy, and human health.
- Identify different ways to address global climate change.

Beijing, a city of 17 million people, has some of the worst air pollution of any major city in the world. When the 2008 Summer Olympic Games were held in the Chinese capital, there was widespread concern over the effect air pollution might have on the athletes as well as spectators attending the games. Some athletes with preexisting health conditions refused to participate, while others caused a stir by arriving at the games wearing protective face masks.

Chinese government leaders took action to address concerns and avoid the possible embarrassment of hosting a major global event shrouded in smog. Two months before the Summer Games were set to begin, heavily polluting factories were shut down, large-scale construction projects were halted or scaled back, and measures were taken to drastically limit the number of cars and trucks on the road. Overall, close to $20 billion was spent to clean up the city's air, and the efforts did appear to have some positive impact. Reduced emissions from cars and factories combined with favorable weather conditions to avert terrible smog conditions, even though most major air pollutants continued to exceed safe levels throughout most of the games.

Aware that China was going to implement these pollution restrictions, scientists and public health experts saw an opportunity to study the effects of air pollution on human health. One such study recruited 125 healthy premedical students in Beijing and began monitoring their heart and lung conditions before the pollution restrictions were put in place, during the restrictions and the period of the Summer Games, and for months afterward. The results of this research were published in the *Journal of the American Medical Association* in 2012 and showed clearly that during the period of the pollution restrictions, the heart and lung conditions of the research subjects improved dramatically (Rich et al., 2012). A different study examined birth weights of babies born in Beijing hospitals before, during, and after the pollution restrictions. It found that women who were 8 months pregnant during the period of the 2008 Summer Olympic Games gave birth to heavier and healthier babies, compared to the other two groups (Rich et al., 2015).

The story of the 2008 Summer Olympic Games is a dramatic example of how pollution can affect human health. And yet it is just one example of how our quality of life worsens when we use the air around us as a dumping ground. This chapter will examine three different environmental challenges that result from our disregard for the air and atmosphere: air pollution, stratospheric ozone depletion, and global climate change. Each challenge has a different cause and operates on a different timescale, geographic scale, and location.

The bulk of this chapter will focus on what is perhaps the most serious of the three challenges and arguably the greatest environmental challenge facing the world today: global climate change. As its name suggests, global climate change is a global problem with no easy, quick fix. In fact, many environmental scientists are worried that our current inaction in the face of global climate change is locking in catastrophic levels of change for the planet for centuries to come.

8.1 Earth's Atmosphere

A recurring theme in this book is the degree to which we tend to take for granted and overlook the natural systems that surround us. That's certainly also the case for our atmosphere. When human populations were small and geographically spread out, pollutant emissions could mix and disperse and not pose much of a problem. However, as our population approaches 8 billion, and as our activities involve ever greater consumption of energy and other material, our impacts on the atmosphere are becoming more severe. To fully understand how human activities lead to air pollution, ozone depletion, and runaway climate change, we need a basic understanding of the atmosphere itself. What is the atmosphere? How does this critical form of natural capital help make life on Earth possible in the first place?

Johnson Space Center/NASA

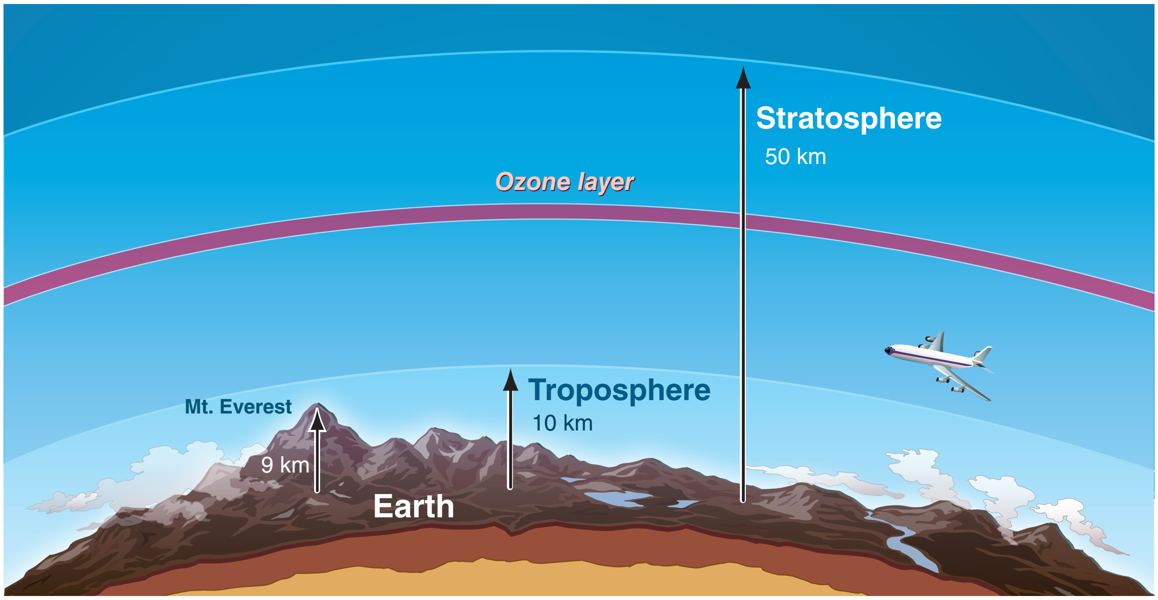
When viewed from the International Space Station, Earth's atmosphere is a thin blue layer over the surface of the planet.

Because our atmosphere cannot really be seen or touched, we often use interesting ways to describe it. Our atmosphere has been called a "thin envelope" or a "thin blanket" of gases surrounding the Earth and held in place by gravity. Despite the atmosphere extending miles into the sky, it's been pointed out that if the Earth were an apple or a peach, the thickness of the atmosphere would be equivalent to the thickness of the skin on those fruits. Our atmosphere provides us with the air we breathe, helps regulate climate in ways that make the planet habitable, and contains gases that filter out dangerous forms of solar radiation that could otherwise make life on the surface of the Earth impossible.

The Earth's atmosphere is divided, from lowest to highest, into four layers—the troposphere, the stratosphere, the mesosphere, and the thermosphere. For the purposes of this chapter, we will focus on the two lowest layers, the *troposphere* and the *stratosphere* (see Figure 8.1).

Figure 8.1: Earth's atmosphere

The troposphere and the stratosphere are the layers of the atmosphere that most directly affect our daily lives.



Troposphere

The **troposphere** ranges in height from 8 kilometers (5 miles) in polar regions where air is cold and dense to 18 kilometers (11 miles) over tropical regions where warm air causes rising air currents. The troposphere is the region of the atmosphere that most directly impacts our day-to-day lives. It's where we live and breathe and is where virtually all the water vapor, clouds, and weather on the planet exist. Air in the troposphere is 78% nitrogen (N_2), 21% oxygen (O_2), and 0.9% argon (Ar). The remaining one tenth of 1% is made up of "trace" gases like carbon dioxide (CO_2), neon (Ne), methane (CH_4), and nitrous oxide (N_2O), as well as water vapor. As we'll discuss, some of these gases, though present in very small quantities, exert an important influence on the Earth's climate system. The top of the troposphere is known as the *tropopause*, something of a boundary between the troposphere and the stratosphere above.

Stratosphere

The **stratosphere** ranges in height from 18 to 50 kilometers (11 to 31 miles) above the Earth's surface. The chemical composition of air in the stratosphere is similar to that of air in the troposphere, with a couple of key exceptions—air in the stratosphere contains almost no water vapor, and it has about 1,000 times more **ozone (O_3)**. While ozone is a dangerous air pollutant near the Earth's surface, it plays a critical role in the stratosphere. Most of the ozone in the stratosphere is concentrated in an area 18 to 26 kilometers (11 to 16 miles) above the Earth in a region known as the **ozone layer**. Ozone molecules in the ozone layer effectively absorb certain wavelengths of incoming ultraviolet (UV) solar radiation that can seriously damage living tissues. For this reason, the stratosphere and the stratospheric ozone layer have been referred to as "Earth's sunscreen." You'll learn more about the ozone layer, and threats to it, in Section 8.3.

Weather Versus Climate

Energy from the sun is constantly striking the atmosphere. About one fourth of this energy is reflected by clouds and the atmosphere back to space, about one fourth is absorbed by clouds and atmospheric gases, and about half reaches the Earth's surface. The solar energy that is absorbed by clouds, atmospheric gases, and surfaces on Earth is reemitted as longer wave infrared or heat energy, warming the air and causing evaporation. This warms the air near the surface and causes it to rise, before that air cools again and sinks. This rising and falling of air creates what is known as **convective circulation**.

Convective circulation patterns help drive the planet's weather, since heat and moisture get moved around the globe in the process. **Weather** consists of the *day-to-day changes* in temperature, atmospheric pressure, precipitation, humidity, and wind. In contrast, **climate** refers to *average* temperature and precipitation patterns in a given area over a longer period, such as a year. As you'll see, confusion over the difference between weather and climate is one of the reasons why global climate change is misunderstood.

8.2 Air Pollution

Air pollution is the presence of substances (air pollutants) in the atmosphere in high enough concentrations to harm humans, other organisms, and inanimate structures such as buildings. Air pollutants can come from natural sources like volcanoes, forest fires, and dust storms, as well as from a variety of human activities. Once in the atmosphere, air pollutants can create problems based on their concentration; how they react with sunlight, water vapor, and other chemicals in the atmosphere; how they are transported from one place to another; and how and where they eventually wash out of the atmosphere (*atmospheric deposition*). The chapter will first examine major sources and types of air pollution and then consider their impacts and possible ways to control and address the air pollution challenge.

Sources and Types of Air Pollution

Environmental scientists typically start by breaking air pollution down into two major categories. **Primary air pollutants** are those that are emitted directly into the atmosphere, such as particulate matter and sulfur dioxide emitted from burning coal in a power plant. **Secondary air pollutants** are formed through chemical reactions in the atmosphere between primary air pollutants and other substances. Environmental scientists also find it helpful to distinguish between air pollutants that come from a *stationary* source like a coal-fired power plant versus those that are emitted by a *mobile* source like a car or truck.

Primary Pollutants

Carbon monoxide (CO) is an invisible, odorless, tasteless gas that results from the incomplete combustion of carbon-based fuels, primarily from motor vehicle exhaust. A second major source of CO is firewood burning and forest fires. Carbon monoxide is dangerous because of its ability to bind to hemoglobin and impair the delivery of oxygen to tissues. Overexposure to carbon monoxide can result in headaches, nausea, fatigue, and ultimately heart damage and death.

Nitrogen oxides (NO_X) include nitric oxide (NO) and nitrogen dioxide (NO_2). Most NO_X emissions come from internal combustion engines in vehicles, as well as from wood burning and forest fires. NO_2 is a reddish-brown gas that can cause lung irritation and respiratory disease; it can also react with water vapor to form a secondary pollutant known as nitric acid (HNO_3). Nitric acid is one of the causes of **acid deposition**, or **acid rain**, which is precipitation—including dust, gas, and fog—that contains acid and falls to the ground. Acid deposition can damage plants, harm aquatic life, and even eat away at statues and the exterior of buildings.

Sebastian Kunigkeit/picture-alliance/dpa/AP Images

Michel Picaud, president of the charity Friends of Notre-Dame de Paris, points out damage caused by acid deposition at the famous Notre Dame Cathedral in Paris, France.

Sulfur dioxide (SO_2) results from the combustion of fuels that contain sulfur, primarily from burning coal in power plants. SO_2 can react in the atmosphere to form a secondary pollutant known as sulfuric acid (H_2SO_4), which also contributes to acid deposition. Sulfur dioxide and sulfuric acid aerosols or droplets reduce visibility, damage crops and trees, corrode metals, damage exterior surfaces, and cause respiratory problems.

Suspended **particulate matter (PM)** refers to a range of solid and liquid particles that are small enough and light enough to remain suspended in the air. Particulate matter can come from natural sources (pollen, spores) as well as from human activities (soot and smoke from fuel combustion, dust from construction projects). Scientists and environmental regulators classify particulate matter into two categories based on their size. Fine particulate matter, or PM-10, are particles with a diameter of 2.5 to 10 micrometers. (For comparison, a typical human hair is roughly 70 micrometers in diameter.) Ultrafine particulate matter, or PM-2.5, are particles smaller than 2.5 micrometers in diameter. Public health experts are particularly concerned about PM 2.5 pollution because smaller particles are more likely to enter deep into the lungs, where they can damage tissue and impair lung, heart, and brain function.

Volatile organic compounds (VOCs) are a range of chemical compounds that originate from both natural sources (e.g., plants) and human activities. VOCs are labeled as “volatile” because they are compounds that can easily become vapors or gases. Major anthropogenic, or human sources, of VOCs include gases that escape from dry-cleaning solvents, gasoline fumes, paint fumes, and plastics manufacturing. VOCs are a major contributor to the formation of ozone pollution, described in more detail later.

Lead (Pb) is a metal, particulate air pollutant that can enter the atmosphere from combustion of leaded fuels as well as from waste incinerators, lead smelters, coal burning, mining, and battery manufacturing facilities. Lead is toxic to the human nervous system and can impede brain functioning and development. Prior to 1986 the main source of atmospheric lead pollution in the United States was leaded gasoline combustion. The phaseout and banning of leaded gasoline in the United States during the 1980s is a regulatory success story, and public health research has confirmed that in the years following the ban, average IQs of children actually increased. Globally, most countries now ban leaded gasoline, although a handful still allow the use of this product.

Ozone

We briefly touched on some secondary pollutants such as nitric acid and sulfuric acid, but one secondary pollutant that needs greater attention is ozone. Ozone (O_3) is formed in the troposphere as a result of reactions between VOCs and NO_x. These chemical reactions need energy from sunlight to occur, so ozone pollution is also referred to as a **photochemical oxidant**. Ozone mixes with other pollutants in the troposphere to form **photochemical smog**.

John Partipilo/The Tennessean/Associated Press

Some cities issue warnings about air quality when the smog is bad enough to affect public health.

Recall that ozone in the stratosphere is "good ozone" and necessary for the survival of life on the planet as we know it. However, ozone near the Earth's surface, in the troposphere where we live and breathe, is a different story. One easy way to remember this distinction is to use the phrase "ozone, good up high, but bad nearby." Down here ozone is "bad." It can cause breathing problems, throat and eye irritation, and coughing and can aggravate heart and lung conditions. Ozone is also damaging to plant tissues as well as human-made materials like fabric, paints, and rubber. It's for these reasons that "ozone alerts" are issued in many metropolitan areas during periods when oz one pollution is bad enough to significantly impact public health. In particular, ozone alert days are especially dangerous to vulnerable population groups like small children, the elderly, and people suffering from respiratory and heart conditions.

Impacts of Air Pollution

It's evident from the review of primary and secondary air pollutants that there are a wide range of known health impacts associated with exposure to air pollution. These include heart and lung damage, respiratory conditions like asthma, brain impairment, and cancer. Some of these conditions are chronic or long term, while others—like an asthma attack or a heart attack—are acute and can occur suddenly.

Because changes to human health are caused by so many interacting factors (environment, diet, genetic traits), it's sometimes difficult to pinpoint the specific impact of any one factor like air pollution. However, by analyzing large population data sets and controlling for other factors, scientists and public health experts are developing a much better understanding of just how significant a role air pollution plays in human health. For example, a 2019 report in the journal *Lancet Planetary Health* estimates that 4 million children worldwide develop asthma every year as a result of air pollution (Achakulwisut, Brauer, Hystad, & Anenberg, 2019). While conditions are worse in countries like India and China, air pollution is still a major contributor to new childhood asthma cases in many parts of the United States as well. A 2019 report by the Health Effects Institute estimated that air pollution will shorten the average expected life span of a child born today by almost 2 years. Likewise, research by the University of Chicago's Energy Policy Institute indicates that the average person alive today would live 2.6 years longer if that person were not exposed to the worst levels of primary and secondary air pollutants described previously (University of Chicago, n.d.). Finally, WHO (2014) estimates that as many as 7 million premature deaths occur worldwide each year as a combined result of outdoor and indoor air pollution.

Air pollution is bad not only for humans but also for other animals and organisms. Plants are particularly sensitive to certain forms of air pollution. It's estimated that tropospheric ozone pollution leads to crop losses of 5% to 15% for major crops like corn, soybeans, and wheat (United Nations Economic Commission for Europe, n.d.). Ozone pollution and acid deposition can also impact forest health and productivity. Trees that are weakened by exposure to air pollution are also less able to withstand pest and disease outbreaks. Finally, air pollution can even impact life underwater in aquatic ecosystems. For example, acid deposition can change the chemistry and pH of lakes and streams. Because many fish and other aquatic organisms are adapted to living in a narrow range of chemical conditions, these changes can stress and even kill them.

Lastly, air pollution can damage exterior surfaces, statues, and buildings. Some of the most obvious effects are aesthetic, since dust, soot, and other particles darken and discolor exterior surfaces. Acid deposition can eat away at limestone and marble statues and building facades and cause them to crumble and erode. Ozone pollution can weaken and deteriorate rubber products like tires and can degrade fabrics and other materials. Acid deposition and other air pollutants can even corrode metal and weaken highways and bridges. A 2014 study in the *American Journal of Engineering Research* estimated that structural corrosion linked to air pollution was costing the Indian economy $45 billion each year (Rao, Rajasekhar, & Rao, 2014).

Addressing Air Pollution

Over the long term, one of the most effective ways to address many air pollution problems is to drastically reduce combustion of fossil fuels and transition to a greater reliance on renewable energy sources. As we saw in Chapter 7, however, that transition is still underway and could take decades to complete. As a result, we still need to take steps to limit air pollution for the immediate future.

One way to reduce air pollution and limit the negative impacts of this environmental challenge is through regulation. The first real federal regulation of air pollution in the United States came in 1955 with the Air Pollution Control Act. This act was spurred in part by "killer smog" events in Donora, Pennsylvania, in 1948 and London, England, in 1952. Both of these events occurred when weather conditions worked to trap heavy air pollution from industries, coal-burning stoves, cars, and trucks in the lower atmosphere. By the time the air cleared, it had killed dozens of people in the small town of Donora and thousands in London, while sickening many more. However, the 1955 Air Pollution Control Act had a very limited impact, and growing public disgust with worsening air pollution prompted the passage of the **Clean Air Act (CAA)** in 1970. The CAA sets air-quality standards for six specific pollutants (carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide), known as **criteria air pollutants**, and then imposes fines and penalizes violators of those standards. Additional amendments in 1977 and 1990 further strengthened the CAA.

Ina Fassbender/picture-alliance/dpa/AP Images

The Clean Air Act prompted the development of the catalytic converter, which reduces pollutant emissions from cars and trucks.

Another regulatory approach that has proved effective in limiting sulfur dioxide pollution is known as **cap and trade**. Under cap and trade, the EPA sets *maximum* allowable levels ("caps") for SO_2 emissions and then issues (or sells) permits to large-scale stationary facilities like coal-fired power plants that emit large amounts of SO_2. These facilities then have to find a way to lower their SO_2 emissions to match the number of permits they have or purchase ("trade") additional permits from facilities that have extra permits as a result of reducing their own SO_2 emissions beyond what they were required to do. The SO_2 cap-and-trade program has proved very effective at reducing sulfur pollution and provides an economic incentive for companies to move "beyond compliance" so that they can be in a position to profit from the sale of extra permits.

As with most forms of regulation, many industries furiously resisted the enactment of the CAA and subsequent amendments. These industries lobbied Congress and launched public relations campaigns arguing that the CAA would harm the economy without necessarily delivering any measurable public health or other benefits. However, one research study after another has shown this position to be wrong. Research conducted by Harvard University scientists in 1993 and 2006 attempted to quantify the public health benefits achieved through CAA regulations (Dockery et al., 1993; Laden, Schwartz, Speizer, & Dockery, 2006). This research showed a clear and unmistakable connection between cleaner air and lower rates of premature death, although it estimated that there are still as many as 75,000 premature deaths each year in the United States as a result of air pollution. A 2011 study by the EPA estimated that from 1990 to 2020 the CAA would impose direct *costs* on the economy of $65 billion. However, over that same period the CAA regulations would yield $2 trillion in *benefits* in the form of reduced illnesses, death, and lost work time. The 30-to-1 benefit–cost ratio in this analysis demonstrates that while environmental regulations might impose some necessary costs on specific industries and economic sectors, they can yield significantly greater benefits to the broader society as a whole.

Regulations like the CAA can also spur innovation and the development of new technologies to help control pollution. For example, most particulate matter from stationary sources like power plants can be controlled by using a device known as an *electrostatic precipitator*. Likewise, *wet scrubbers* can be used to remove PM and SO_2 pollution from stationary sources. In terms of mobile sources like cars and trucks, the CAA prompted the development of a key piece of technology known as the *catalytic converter*. Catalytic converters reduce pollutant emissions from cars and trucks by 90%. As a result, and even though vehicle miles driven have more than tripled since 1970, air pollution from mobile sources is actually significantly lower today than it was decades ago.

Overall, while dramatic progress has been made in reducing the impacts of air pollution in countries like the United States over the past 50 years, this is not the case everywhere. Rapidly growing emerging economies like China and India are grappling with far more serious air pollution levels. And even in the United States and other developed countries, air pollution still takes a toll on public health, the environment, and infrastructure. As we'll discuss, addressing the air pollution challenge by reducing levels of fossil fuel use will also help address the challenge of global climate change—another of those win–win scenarios.

8.3 Stratospheric Ozone Depletion

The gradual formation of the ozone layer over 1 billion years ago represents one of the single most important preconditions for the evolution of life on land. Prior to that, Earth's surface was constantly being bombarded with UVB and UVC radiation. This UV radiation is carcinogenic and mutagenic, so the surface of the planet was mostly devoid of life.

The only protection from this radioactive bombardment was underwater, and it's there that single-celled marine bacteria and algae first emerged. Recall that marine bacteria and algae are capable of photosynthesis and that one by-product of photosynthesis is oxygen. As the numbers of these organisms increased, there was a gradual buildup of oxygen in the atmosphere. When an oxygen (O_2) molecule is struck by UVB or UVC radiation, it splits into two free oxygen atoms ($O + O$). These free oxygen atoms are then available to combine with an oxygen molecule to form ozone ($O + O_2 = O_3$). Over hundreds of millions of years, as oxygen levels increased in the atmosphere, so did levels of ozone, resulting in the formation of the ozone layer.

Ozone in the stratosphere shields us from harmful UV radiation by undergoing a constant process of destruction and re-creation. Incoming UV radiation strikes an ozone molecule and breaks it apart into O and O_2, but in the process the energy in that UV radiation is used up and dissipated as heat. After that, the free O can recombine with O_2 to once again form O_3. It's believed that this constant cycle of ozone creation and destruction has been going on in the stratosphere for over 1 billion years. Much like aquifer recharge (Chapter 5), this ozone creation–destruction process can be likened to a bathtub filled with water, with the faucet on but the drain also open. As long as the water is flowing into the bathtub (ozone creation) at the same rate it is being drained out (ozone destruction), the level of water in the bathtub (or ozone in the stratosphere) will remain in a dynamic equilibrium.

Causes of Ozone Depletion

It's only in the past 100 years that human activities have thrown off that dynamic equilibrium. **Stratospheric ozone depletion** is often confused with climate change, with some thinking that the resulting "hole" in the ozone layer was responsible for letting in more heat. In fact, stratospheric ozone depletion is fundamentally a separate issue from climate change: Recall that less ozone means more UV radiation, not more heat. The two problems are related only because they are both the result of human-generated chemicals in the atmosphere.

In the case of stratospheric ozone depletion, the issue stems from the development, mass production, and pervasive use of a class of chemicals known as **ozone-depleting substances**. Chief among these substances is a product known as **chlorofluorocarbons (CFCs)**. CFCs were first invented in the 1920s as a refrigerant and a propellant for spray cans, but they did not come into widespread production until the 1950s. CFCs offered a number of advantages over other chemicals being used for these applications at the time—namely that they were nontoxic, inexpensive to produce, light, and extremely stable and chemically nonreactive. The latter two characteristics are what led to CFCs becoming a culprit in stratospheric ozone depletion. Because CFCs are so light, they tend to float upward once released to the atmosphere. And because CFCs are stable and nonreactive, they do not chemically react or wash out of the atmosphere once put there. As CFCs came into greater and greater use, more of these chemicals were being released into the atmosphere, where they slowly floated toward the stratosphere.

In some ways the fact that CFCs seemed to float away made them an ideal chemical compound. However, recall that in nature “there is no away” and that “everything must go somewhere” (Commoner, 1971, p. 39). It was this basic understanding of nature that led scientists to begin to ask questions about the fate of increasing levels of CFCs being released to the atmosphere. In 1973 atmospheric scientists Mario Molina and F. Sherry Rowland began to speculate that CFC molecules could be reaching the stratosphere, where extremely intense UV radiation would be strong enough to break them apart. A single chlorine atom broken free from a CFC molecule would then be available to react with and “destroy” an ozone molecule in a cycle that could repeat itself thousands of times over. To return to the bathtub analogy, the introduction of CFCs and chlorine to the stratosphere was the same as widening the drain—resulting in declining levels of ozone in the stratosphere. Rowland and Molina’s theory that chlorine from CFCs could be destroying the protective ozone layer got a lot of media attention, but industries dependent on CFCs pushed back strongly and argued that there was no evidence that such a situation was occurring.

It wasn’t until 10 years later that scientific teams using weather balloons to measure atmospheric chemistry over Antarctica first reported substantial declines in levels of stratospheric ozone. Soon after, a satellite-based ozone mapping instrument confirmed large losses of ozone over the poles, and the idea of an “ozone hole” and increased risk for skin cancer grabbed the public’s attention. In the late 1980s and early 1990s, further satellite measurements revealed stratospheric ozone losses of as much as 15% over heavily populated regions of the Northern Hemisphere.

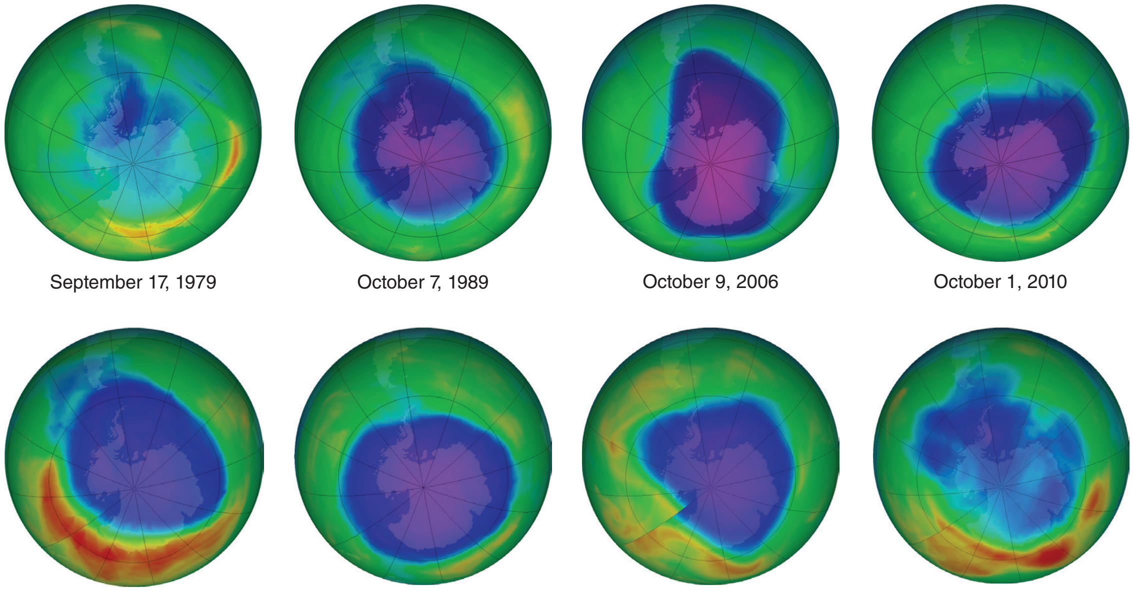
Addressing Ozone Depletion

Because even a 1% decline in stratospheric ozone can result in a 2%–4% increase in cases of skin cancer as well as other health problems like cataracts, there was tremendous public pressure on governments to act. In 1987, 45 of the world’s largest economies agreed to what became known as the **Montreal Protocol**. The Montreal Protocol originally called for a 50% reduction in CFC use by 1998, but after further research showed ozone loss accelerating, this was changed to a complete phaseout of CFCs by 1996. Eventually, more than 180 nations signed the Montreal Protocol, and this agreement is still the basis for global efforts to protect the ozone layer today.

The stratospheric ozone depletion issue is one of the rare “good news” stories in the environmental field. Over the past 2 decades, stratospheric ozone concentrations have begun to stabilize and are now even beginning to return to previous levels in some locations. While the ozone loss remains significant (see Figure 8.2), scientists estimate that if current trends hold, the entire ozone layer could completely “heal” by 2060 (Reiny, 2018).

Figure 8.2: Ozone hole

NASA has been monitoring the ozone layer for decades. Blue and purple represent areas where there is the least ozone. Red and yellow show where there is the most ozone. While the ozone hole has begun to repair itself, it still has a ways to go.



September 17, 1979 | October 7, 1989 | October 9, 2006 | October 1, 2010

September 17, 2014 | October 2, 2015 | November 4, 2018 | August 21, 2019

*Source: “NASA Ozone Watch,” by National Aeronautics and Space Administration, n.d. (**https://ozonewatch.gsfc.nasa.gov/monthly/SH.html**).*

The ozone depletion issue offers us a number of important lessons about how to deal with potentially catastrophic and global environmental challenges. First, we should always remember the basic environmental rules of “there is no away” and “everything must go somewhere” (Commoner, 1971, p. 39). Second, scientific uncertainty and the complexity of global-scale environmental issues should be no excuse for inaction when the stakes are so high. Third, we should expect that private businesses and some of the politicians they lobby will use scientific uncertainty and the media to cast doubt on the seriousness of a given issue. Finally, global environmental challenges require global solutions. These lessons will be important to keep in mind as we examine an even greater threat to the planet in the next section—global climate change.

8.4 Earth’s Climate System

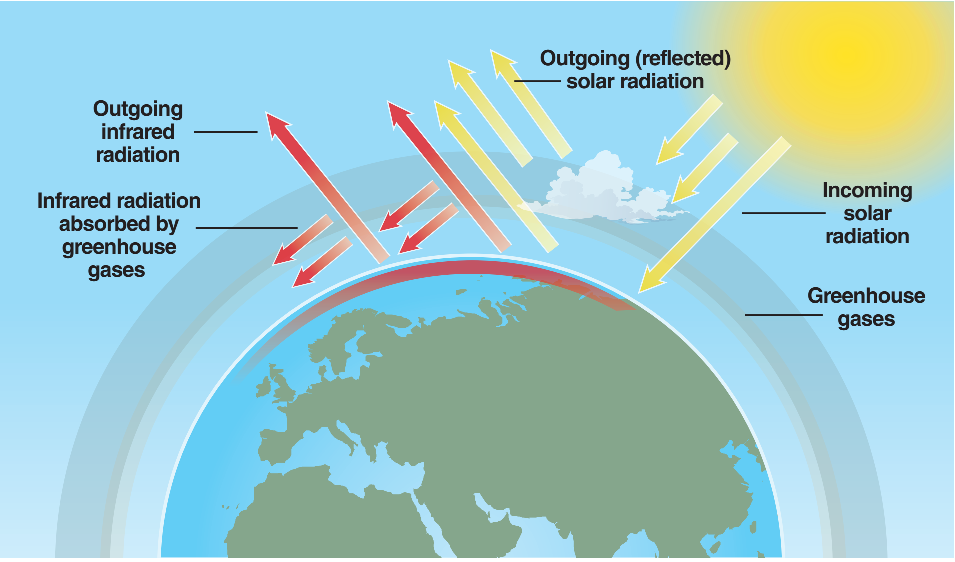
One way to think about the Earth’s climate is to use the analogy of a house in the middle of the winter. All houses lose heat through walls, windows, doors, and the roof in winter months, so how do these houses stay warm? A source of heat (a furnace or space heater) applies enough warmth at the right rate to offset the heat being lost. In other words, the house is in an **energy balance**, and a constant temperature can be maintained.

The same principle is at work for Earth and other planets. In this case energy, in the form of solar radiation or sunlight, strikes the Earth and warms it. Eventually, that energy escapes back to space as longwave radiation or heat following fundamental laws of physics, and the Earth is in an energy balance. Based solely on this process of incoming solar radiation and outgoing longwave radiation, scientists can predict that the average surface temperature on Earth over the entire year should be –18 °C (0 °F). In reality, the Earth's average surface temperature over the entire year is closer to 15 °C (59 °F). What could explain this difference?

The reason for the 33 °C difference between predicted and actual temperatures on Earth is because of our atmosphere and what is known as the **greenhouse effect**, best explained through Figure 8.3. Scientists estimate that, *on average*, the amount of solar energy reaching the Earth's atmosphere every second is 340 watts per square meter. For the sake of simplicity, we will use a generic figure of 100 solar energy units reaching the atmosphere. Of those 100 units, about 30 are reflected back into space by clouds, airborne aerosol particles, and ice, snow, and light-colored land on the Earth's surface. About 70 units are absorbed by the atmosphere or by land and water on the surface of the Earth and then reradiated as infrared or heat energy. Some of this heat energy passes back through the atmosphere and is lost to space, but much of it is absorbed by **greenhouse gases**—the term for gases that absorb infrared radiation—and then reemitted as heat back toward the surface. This helps warm the Earth's atmosphere. The layer of greenhouse gases in the atmosphere acts like the windows in a car or a greenhouse on a sunny day—hence the term *greenhouse effect*. The greenhouse gases allow incoming solar radiation to pass through, but they trap outgoing heat energy and warm the surface of the planet.

Figure 8.3: Greenhouse effect

While some incoming solar radiation is reflected back into space, much is absorbed by Earth's atmosphere, land, and water and reradiated as infrared radiation, or heat energy. Some of that heat is lost to space, but much of its absorbed by greenhouse gases and reemitted back to the surface. The greenhouse effect is a naturally occurring phenomenon that has intensified due to humans adding more greenhouse gases to the atmosphere.



*Source: Adapted from "Human Influence on the Greenhouse Effect," by GlobalChange.gov, n.d. (**https://www.globalchange.gov/browse/multimedia/human-influence-greenhouse-effect**).*

Returning to the analogy of the home and energy balance, greenhouse gases and water vapor in the atmosphere are akin to walls in that they help *retain* some of the heat in the home before it is eventually lost. In the case of our planet, it does not get hotter and hotter with each passing day, because energy is always escaping. As the sun goes down, heat energy built up near the Earth's surface gradually dissipates back into space. This is why the coldest time of day is usually just before dawn and why cloudy nights (when water vapor is present) are less cold than clear nights. In other words, the Earth is in energy balance between incoming solar radiation and outgoing infrared or heat energy. Greenhouse gases and water vapor *naturally* retain some of that outgoing heat energy long enough to keep the lower atmosphere about 33 °C warmer than it would otherwise be.

Given the beneficial role that greenhouse gases and the greenhouse effect play in moderating climate and making our planet habitable, why are we so concerned about greenhouse gas emissions from fossil fuel combustion and other human activities? As we'll discuss, rising concentrations of greenhouse gases in the atmosphere are resulting in an *enhanced* greenhouse effect and global warming. Returning once again to our house analogy, rising greenhouse gas concentrations are like adding insulation to the walls while still supplying the same amount of heat from a furnace. The result is that Earth is warming in ways that may not be beneficial for us or other organisms that make this planet home.

8.5 Global Climate Change

The reality and importance of the natural greenhouse effect cannot be called into question. Without it, Earth would have an average surface temperature that would result in most of the planet being permanently covered in snow and ice. Our real concern, from an environmental standpoint, is that human activities are enhancing that greenhouse effect and resulting in "global warming" as the atmosphere and oceans rise in temperature. This warming is driving changes in climate—in average precipitation patterns, air currents, humidity, and other factors—and so scientists prefer to use the term **global climate change** to describe these worldwide trends.

However, humanity's role in global climate change is frequently called into question in political debates. This section, therefore, will focus on two critical questions. First, is the Earth actually warming? Second, and most critical, are human actions responsible for any warming, or is this just part of natural climate variability?

Is the Earth Warming?

The Intergovernmental Panel on Climate Change (IPCC, 2014), the world body charged with providing an objective and scientific review of climate change, states that recent warming of the planet is beyond a doubt:

> *Human influence on the climate system is clear, and recent anthropogenic [human] emissions of greenhouse gases are the highest in history. . . . Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and*

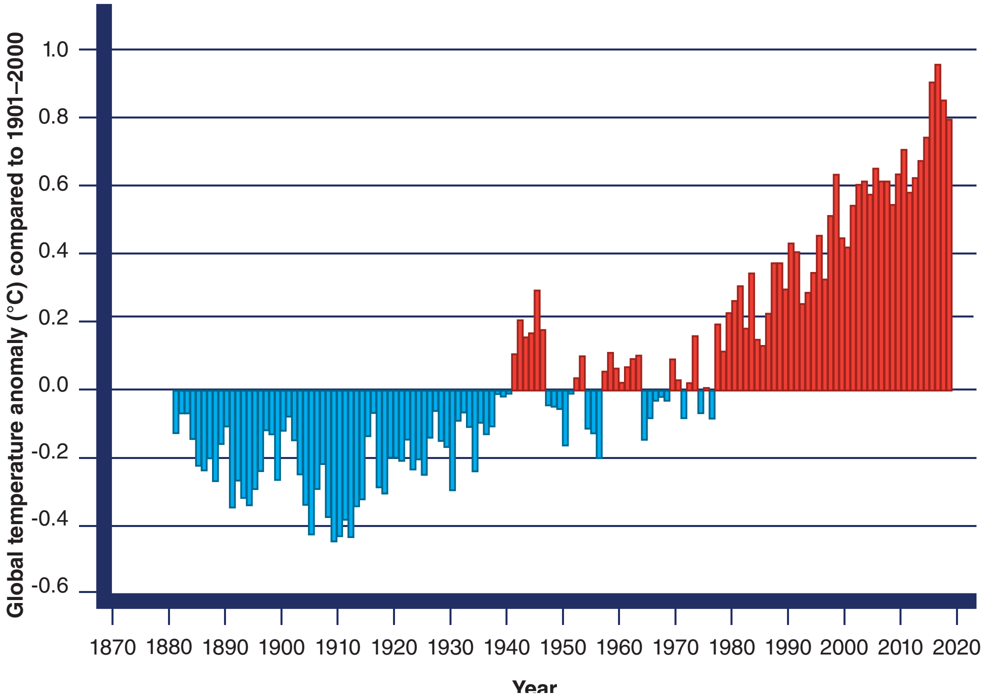
> *ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen.* (p. 2)

The IPCC goes on to confirm that each of the past 3 decades have been successively warmer than any preceding decade and that the period from 1983 to 2012 was likely the warmest 30-year period in the past 1,400 years. Things have only gotten worse since then—the four warmest years on record, in order, are now 2016, 2017, 2015, and 2018. In addition, July 2019 is now the warmest month in recorded history.

The IPCC bases its conclusion on a wide range of evidence. First, scientists, meteorologists, and regular citizens have been measuring and recording local temperatures all over the world for centuries. Regular and consistent measurements of surface temperatures over wide areas of the globe did not begin, however, until roughly 150 years ago. Those temperature measurements have been plotted against an average temperature to show temperature anomalies or deviations over time. Figure 8.4 displays temperature trends over land and ocean since 1880 relative to the 1901–2000 average and illustrates that the planet has warmed about 1 °C (1.8 °F) over that time period. The global network of thermometers used to record this temperature data has come under criticism for a variety of reasons having to do with consistency of measurement and other possible biases. However, climate scientists regularly review and modify the data provided by these thermometers to factor in those biases, and this surface temperature record is considered highly reliable as a result.

Figure 8.4: Global mean temperature over land and ocean, 1880–2017

This graph showing deviations from the average global temperature over time indicate that the Earth today is about 1 °C warmer than the 1901–2000 average.

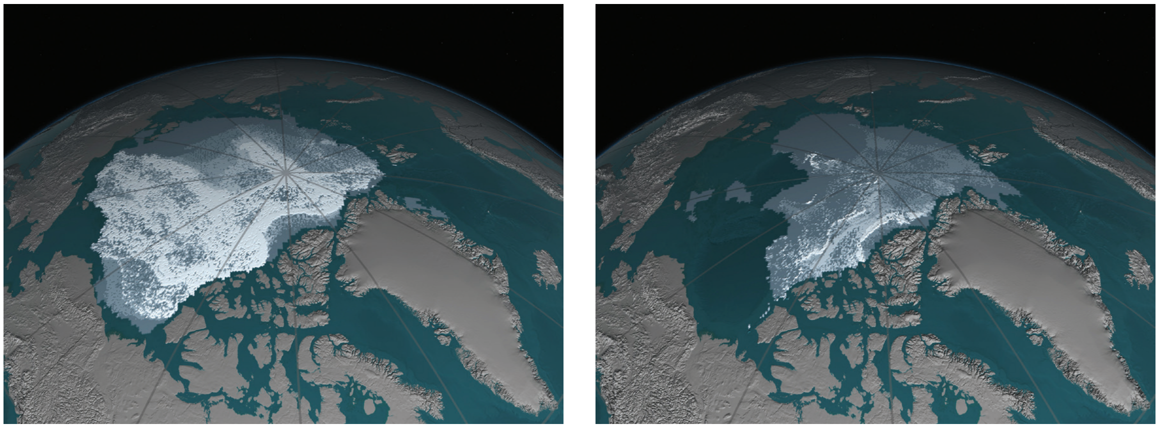


*Source: Adapted from "Climate Change: Global Temperature," by R. Lindsey and L. Dahlman, 2018 (**https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature**).*

We know from the scientific method, however, that scientists prefer to have data from multiple sources before making conclusions, and the issue of climate change is no different. Starting in 1978 climate scientists began to use satellite-based instruments to measure average temperature for the bottom 8 kilometers (5 miles) of the atmosphere, confirming the warming trend detected by surface thermometer readings. More importantly, National Aeronautics and Space Administration (NASA) climate scientists published a report in *Environmental Research Letters* in April 2019 that showed that satellite-based temperature measurements were "highly consistent" with information collected by surface-based thermometers (Susskind, Schmidt, Lee, & Iredell, 2019). The close consistency of the satellite temperature measurements with surface temperature records significantly increases the certainty of climate scientists that our planet is actually warming.

In addition to surface thermometer and satellite-based temperature measurements, scientists point to a number of other pieces of evidence to confirm that the Earth is, in fact, warming. First, scientists have been monitoring close to 200 glaciers around the world since as early as 1860. In that time period, only three of the glaciers studied actually advanced or increased in size, while 177 retreated and became smaller (Lindsey, 2018b; Zemp et al., 2019). Second, scientists have been using satellite imagery to monitor the extent of sea ice since the mid-1970s. In that time sea ice coverage has declined, especially over the Arctic region (NASA, 2019a; National Snow & Ice Data Center, 2018).

Third, scientists have also been monitoring the two largest ice sheets on the planet, one covering most of Greenland and the other on Antarctica. These two ice sheets are massive (almost 3.2 kilometers, or 2 miles, thick in some locations) and contain most of the world's freshwater supply. Satellite measurements begun in 2002 show that these ice sheets have lost 200 billion metric tons or more of ice every year and over 1 trillion metric tons of ice since measurements began (National Snow & Ice Data Center, n.d., NASA, 2019c, Mouginot et al., 2019).



NASA Earth Observatory

The area covered by Arctic sea ice at least 4 years old has decreased from 1.9 million square kilometers (718,000 square miles) in September 1984 (left) to 110,000 square kilometers (42,000 square miles) in September 2016 (right). The oldest ice—represented by white—is the least vulnerable to melting away.

Fourth, as discussed in Chapter 6, ocean temperatures are increasing dramatically worldwide as oceans absorb much of the extra heat being trapped by higher concentrations of greenhouse gases. Finally, sea levels are rising as a result of global warming for two reasons—ocean water expands as it warms, and melting ice from glaciers and ice sheets adds water to the oceans. Sea level measurements date back over 100 years and confirm that sea level has been rising steadily during that time and that the *rate* of sea level rise has increased sharply in the past couple of decades (NASA, 2019d; Lindsey, 2018c).

Taken together—surface thermometer records, satellite temperature readings, and observations of glaciers, sea ice, ice sheets, ocean temperatures, and sea levels—*all evidence points clearly and unequivocally to the observation that the world is, in fact, in the process of warming*.

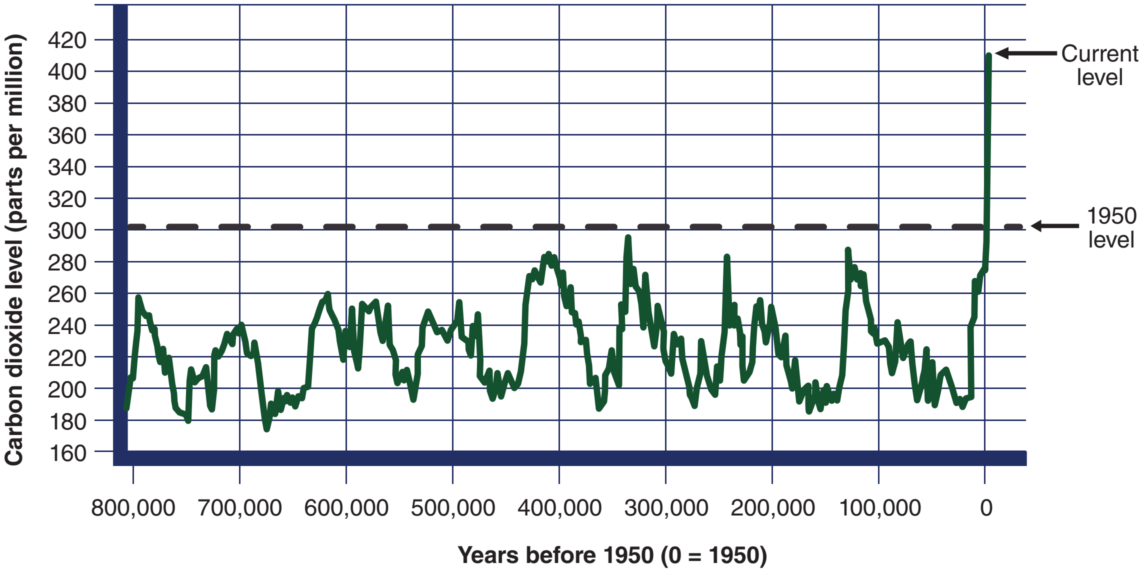
Are Humans Responsible?

The next question to consider is to what extent the observed warming of the planet is due to human activities rather than some sort of natural cause. Scientists refer to this question as one of *attribution*: In other words, to what factor(s) can the observed warming be attributed? One of the best ways to determine whether human actions are mainly responsible for global warming is to consider and review *other factors* that have been known to change climate in the past. For example, movement of the Earth's continents over geologic timescales has changed the climate in the past. Likewise, changes in Earth's orbit affect how sunlight is distributed around the planet and are known to have caused ice ages in the past. However, both continental movements and orbital variations occur on timescales of thousands to millions of years, and so neither of these can explain the observed warming of the past 150 years. Another possible nonhuman cause of climate change could be changes in the amount of energy reaching our planet from the sun. Scientists have been using satellite-based instruments to measure solar output (known as the solar constant) since 1970, and that research shows that solar energy reaching Earth does vary on an 11-year cycle. However, there has been no long-term increase in the solar constant since 1970, and so this explanation for a warming planet also does not hold up.

The one scientific explanation for recent global warming trends that is highly consistent with the observed warming of the past 150 years is the increase in atmospheric concentrations of greenhouse gases. Recall from the discussion of the greenhouse effect and the atmosphere that small quantities of greenhouse gases in our atmosphere exert a strong influence over climate. The basic physics of how greenhouse gases warm the planet was established close to 200 years ago, and our understanding of their role has only strengthened since then. In addition, scientific research that uses ice cores, mineral deposits, and radiocarbon dating of ancient pollen levels demonstrates an extremely strong correlation between the temperature of the Earth and levels of the greenhouse gas carbon dioxide (see Figure 8.5). The Earth has experienced a number of "greenhouse periods" over the past 800,000 years, with these episodes being caused by increased volcanic activity, changes in solar output, and other natural causes that occurred over tens of thousands of years. What's different about the current period of warming is that human activities are the cause, and it's happening faster than it ever has in the past.

Figure 8.5: Temperatures and carbon dioxide

Atmospheric carbon dioxide concentrations in parts per million (ppm) for the past 800,000 years, based on EPICA (ice core) data. The peaks and valleys in carbon dioxide levels track the coming and going of ice ages (low carbon dioxide) and warmer interglacials (higher levels). Throughout these cycles, atmospheric carbon dioxide was never higher than 300 ppm; in 2017 it reached 405 ppm.



*Source: Adapted from "Climate Change: How Do We Know?" by Global Climate Change: Vital Signs of the Planet, n.d. (**https://climate.nasa.gov/evidence/**).*

Human activities are leading to increased atmospheric concentrations of four important greenhouse gases. **Carbon dioxide (CO_2)** comes mainly from combustion of fossil fuels as well as from deforestation and other land-use changes. **Methane (CH_4)** comes mainly from agricultural activities like rice farming and cattle production, as well as from leaks from natural gas pipelines and drilling facilities. **Nitrous oxide (N_2O)** comes from fertilizer use and fossil fuel combustion. **Halocarbon gases**, including the CFCs implicated in ozone depletion, also act as a greenhouse gas in the troposphere.

For now, let's zero in on carbon dioxide because it is the most abundant greenhouse gas emitted by human activities. (For more on the other greenhouse gases, see the *Apply Your Knowledge* feature.) We know from Chapter 7 that the carbon contained in fossil fuels like coal, oil, and natural gas comes from organic material that lived and died hundreds of millions of years ago. When we mine and burn these fuels, we are *moving* carbon from one place (deep geologic storage) to another (the atmosphere).

Human emissions of CO_2 are relatively small compared to natural sources of this gas. As part of the carbon cycle, plant respiration and decomposing vegetation release close to 100 billion metric tons of carbon each year, and oceans release another 90 billion metric tons. By comparison, human activities are responsible for the release of only about 7 billion to 8 billion metric tons of carbon (equivalent to about 30 billion metric tons of CO_2) each year.

However, natural sources of carbon are balanced out by natural **sinks**—natural processes that absorb and store carbon. Just as much CO_2 is absorbed by plants through photosynthesis as is released through respiration and decomposition. In contrast, human sources of CO_2 are not balanced by sinks, and that is why they result in gradual increases in atmospheric CO_2 levels. Preindustrial concentrations of CO_2 were 280 ppm but are now well over 400 ppm. Likewise, atmospheric concentrations of methane and nitrous oxide have followed a similar trend. In terms of attribution, then, there is little question that the observed warming of the past 150 years is due primarily to human activities in the form of increased greenhouse gas emissions.

As increased greenhouse gas concentrations lead to more warming of the oceans and Earth surfaces, scientists worry about the possibility of secondary impacts or feedback effects. It's true that some feedback effects could counteract global warming. Consider the formation and distribution of clouds. As the Earth warms, we expect there to be more evaporation and more water vapor in the atmosphere as a result. That increased water vapor could result in more cloud cover, which would reflect more incoming sunlight back to space and possibly cool the planet. On the other hand, water vapor itself is a powerful greenhouse gas, and more of it in the atmosphere could lead to greater warming.

It's not clear to what extent these two cloud-based feedback effects will cancel each other out, but what is clear is that most of the possible feedback effects that scientists are aware of will make things worse. For example, recall from Chapter 2 that large areas of the Arctic are made up of what is known as *permafrost*. These areas are essentially frozen swampland, and they contain a massive amount of carbon dioxide and methane that's frozen in place. As permafrost regions have become warmer and begun to thaw, they are releasing that CO_2 and CH_4 to the atmosphere, worsening global warming and thawing even more permafrost in a "feedback" cycle that's become known as a "carbon bomb" or "methane bomb." Likewise, we know that light-colored surfaces like ice and snow reflect incoming solar radiation back to space, rather than absorbing it. In scientific terms, ice and snow have a high **albedo**, or degree of reflection. As global warming causes more ice and snow to melt, it reveals surfaces that are darker in color and that absorb more incoming solar radiation; that is, surfaces that have low albedo. This causes even more warming and even more ice and snow melting in a feedback cycle known as the *ice-albedo feedback loop*.

Apply Your Knowledge: What About the Other Greenhouse Gases?

When we discuss climate change, our conversations often focus on CO_2 emissions, but what about the other greenhouse gases mentioned in this chapter? Should we be concerned about releasing materials like methane and nitrous oxide too? We will explore these greenhouse gases in greater detail so that we can identify the ones that pose the greatest threat to the environment.

(continued)

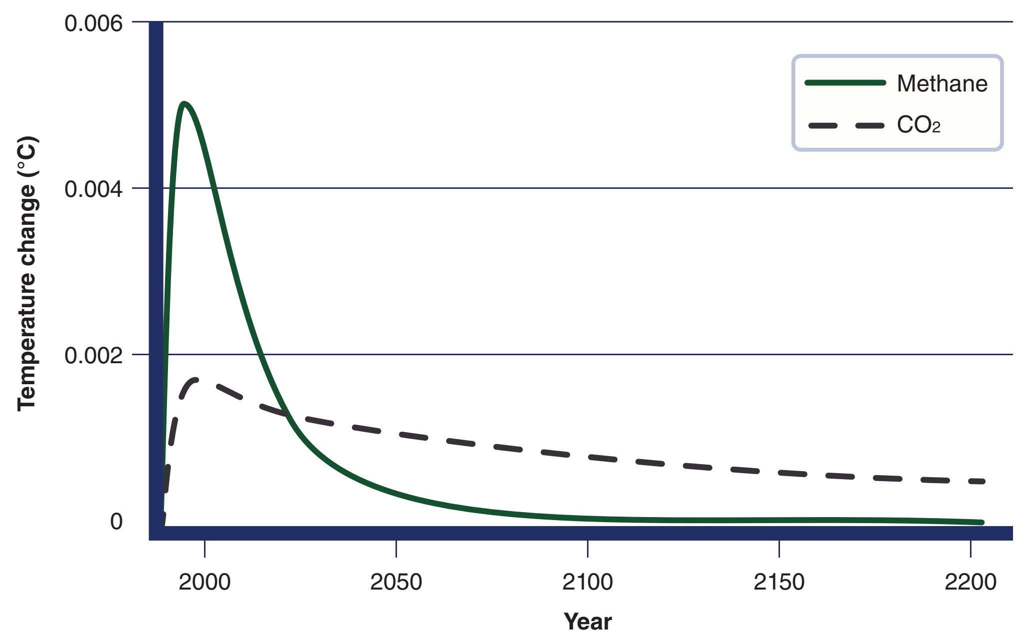
Apply Your Knowledge: What About the Other Greenhouse Gases? *(continued)*

To begin our analysis, try to imagine how the Earth's temperature might respond to releasing a large pulse of greenhouse gas emissions all at once. At first, we would see significant warming, but over time, we might expect the quantity of greenhouse gases in our atmosphere to change. Methane molecules, for example, react with other materials in the Earth's atmosphere, and if no further emissions were produced, excess levels of methane would decrease over time. Similarly, nitrous oxide molecules would eventually break down from UV radiation, and even though it takes a really long time, excess levels of CO_2 can be sequestered by oceans and geologic formations in the absence of new emissions. If we take all this into consideration, we might expect temperatures to eventually recover from an isolated period of emissions.

We can see this process in action in Figure 8.6. In this chart, simulated temperature changes are plotted against time for large releases of methane and CO_2. In both cases we expect temperatures to rise immediately after the gases are emitted, and in both cases temperatures begin to recover as excess levels dissipate.

Figure 8.6: Temperature changes of isolated greenhouse gas emissions

Notice the difference in potency and longevity between carbon dioxide and methane.



Source: Data from "The Jury Is Still Out on Global Warming Potentials," by B. C. O'Neill, Climatic Change, 44.

(continued)

Apply Your Knowledge: What About the Other Greenhouse Gases? *(continued)*

If you study the curves more closely, you might also notice two important differences between the two gases. First, the methane emissions result in a larger temperature spike than the CO_2 emissions. This is because the chemical structure of methane is much better at trapping energy than that of CO_2. This leads to more warming in the short term. Second, the temperature recovers more quickly from the methane emissions. This happens because methane is more easily removed from the atmosphere than CO_2. While most excess methane will be gone after a couple of decades, excess levels of CO_2 can hang around for hundreds or even thousands of years. From our analysis, we can begin to understand how the potency and the longevity of greenhouse gases are both important characteristics to consider when trying to understand their environmental impacts.

To help us consider both strength and endurance when comparing greenhouse gases, scientist developed a metric called Global Warming Potential (GWP). GWP is the total amount of energy trapped by a greenhouse gas over a specified time horizon. Given the data in Figure 8.6, we might expect methane to have a larger GWP than CO_2 over a shorter time period because it causes much more short-term warming. However, if we were to consider a really long time horizon, CO_2 might end up trapping more heat than the short-lived methane.

To make GWP values easier to interpret, they are always calculated relative to CO_2. In other words, CO_2 will always have a GWP equal to 1 regardless of the time horizon being considered. If another gas has a GWP of 10, then that gas will trap 10 times more energy than CO_2 over that period.

Take a look at the GWP values in Table 8.1 that describe CO_2, methane, and nitrous oxide emissions over several different time horizons. Based on these values, how does CO_2 compare to methane and nitrous oxide?

Table 8.1: GWP and lifetimes of CO_2, methane, and nitrous oxide

		GWP		
Greenhouse gas	**Lifetime in years**	**20 years**	**100 years**	**500 years**
CO_2	Variable	1	1	1
Methane	12	72	25	7.6
Nitrous oxide	114	289	298	153

Source: Data are from "2007: Changes in Atmospheric Constituents and in Radiative Forcing," by P. Forster, V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey . . . and R. Van Dorland, in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt . . . and H. L. Miller (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change *(p. 212), 2007, Cambridge, United Kingdom: Cambridge University Press (https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf).*

(continued)

Apply Your Knowledge: What About the Other Greenhouse Gases? *(continued)*

You might be wondering why we talk so much about CO_2 when methane and nitrous oxide appear to be stronger greenhouse gases for all time horizons. One important reason is that we emit a lot more CO_2 than we do methane or nitrous oxide. In fact, we emit hundreds of times more CO_2 than we do methane and thousands of times more CO_2 than nitrous oxide. In total, CO_2 emissions are responsible for about 80% of the warming caused by humans.

That being said, other greenhouse gases like methane and nitrous oxide are still responsible for 20% of climate warming, and this is because of their high GWPs. CO_2 is public enemy number one, but we should probably be concerned about all three greenhouse gases if we want to address climate change. Luckily, we can reduce the emissions of all three greenhouse gases at the same time by transitioning away from fossil fuels and improving farming practices.

Why the Debate?

A number of global surveys of public opinion have shown that Americans are generally less well informed and less worried about global climate change compared to residents of other countries. One possible source for this situation is the way in which climate change science is presented in the American media. Because journalistic standards call for balance in coverage of an issue, media outlets will frequently try to give both sides to any story about climate change or its impacts. And because there are powerful financial interests, such as fossil fuel companies, opposed to policies to address climate change, media outlets are able to find individuals who will question whether climate change is happening and whether it is a serious threat.

A helpful way to approach the scientific, economic, political, and ethical debates over climate change is to consider the difference between arguments that are based on *positive claims* versus those based on *normative claims*. A positive claim is a statement about *what we know*, while a normative claim is a statement about *what we value*.

When a climate scientist makes a claim that atmospheric concentrations of greenhouse gases are increasing or that ocean temperatures are rising, these are *positive claims*, statements about *the way things actually are*. When a politician makes a claim that we need to tax fossil fuels to help address climate change, that is a *normative claim*, a statement about the *way things should be*, at least in the view of that politician. While the results of scientific research have political implications, the scientific process itself is not political. (Recall the discussion of the scientific method in Chapter 1.) Instead, scientists are guided by a set of principles that keep them focused on trying to understand the way the world works.

"Gentlemen, it's time we gave some serious thought to the effects of global warming."

Mick Stevens/Cartoon Collections

There is now broad scientific consensus and an overwhelming body of evidence that *the planet is warming* and that *human activities are responsible for this warming*. There is also strong and growing evidence that some of *the impacts of this warming could be catastrophic* to human and natural systems. These are positive claims, statements about *the way things actually are*. As a result, the real debate at this point should be about *how* and *when* we should respond to climate change, *who* will pay for that response, and whether we should focus mainly on *preventing* further warming or trying to *adapt* to an already changing climate. These are normative debates, arguments about the way the world should be.

The remainder of this chapter focuses on the impacts and possible solutions to what is arguably the single most critical issue in environmental science today. We can say this for a couple of reasons. First, global climate change is just that, global. The impacts of climate change on food, water, human health, weather, and other aspects of our lives are already impacting everybody on the planet. Likewise, the necessary responses and solutions to climate change—in terms of energy use, transportation, and diet—will also touch everyone's lives. Second, global climate change is potentially irreversible, and many scientists worry that we are on the brink of (or already past) a tipping point. Human society has evolved and adapted to our current climate state, and so a sudden shift to a new climate state could be catastrophic at many levels.

Learn More: Climate Change Myths

Katharine Hayhoe is an atmospheric scientist, director of the Climate Science Center at Texas Tech University, and one of the lead authors of the U.S. Global Change Research Program's (USGCRP) *Fourth National Climate Assessment*. In late 2018 Hayhoe wrote a short opinion column that was published in a number of major newspapers around the country titled "Five Myths About Climate Change" (Hayhoe, 2018a, 2018b). In that piece, Hayhoe describes the myths and addresses why they are wrong. A simple summary of those five myths and Hayhoe's refutation of them looks like this:

- Myth 1: Climate scientists are "in it for the money." In reality, climate scientists like Hayhoe could be making far more money working in the private sector, such as for an oil company. The relatively small amount of money that climate scientists collect for their work is used to support their laboratories, graduate students, and other aspects of their work.
- Myth 2: The climate has changed before; it's just a natural cycle. As we just saw, while the climate has changed before and does go through natural cycles, none of the factors that have caused earlier changes can explain what we are experiencing now.
- Myth 3: Climate scientists are split on whether warming is real. In reality, more than 97% of climate scientists agree that global warming is happening and that humans are causing it (NASA, 2019b).
- Myth 4: Climate change won't affect me. While only 40% of Americans think climate change will harm them personally, the wide range of impacts described in the next section will likely affect everyone.
- Myth 5: It's cold outside, so global warming can't be real. This confuses weather and climate. As Hayhoe points out, weather is like your mood, while climate is your personality. Occasional bouts of very cold weather in some regions of the world do nothing to refute the larger trend of increasing temperatures worldwide.

You can read Hayhoe's full column at either of the following publications. Hayhoe is also an evangelical Christian and the coauthor of *A Climate for Change: Global Warming Facts for Faith-Based Decisions*.

- https://www.chicagotribune.com/opinion/commentary/ct-perspec-climate-change-five-myths-hayhoe-1209-20181206-story.html
- https://www.washingtonpost.com/outlook/five-myths/five-myths-about-climate-change/2018/11/30/9fba233a-f428-11e8-bc79-68604ed88993_story.html

8.6 Impacts of Global Climate Change

In November 2018 the USGCRP (2018), made up of scientists from 13 federal government agencies, issued its *Fourth National Climate Assessment* (Reidmiller et al., 2018). Despite its release on the Friday after Thanksgiving, the report received widespread media coverage and generated dramatic headlines. Some of the most alarming forecasts in the report had to do with massive economic losses and thousands of additional premature deaths caused by climate change each year. But more importantly, the USGCRP firmly established the reality of global climate change and the fact that it is *already* impacting the United States and other nations around the world. David Easterling, a National Oceanic and Atmospheric Administration (NOAA) scientist and one of the authors of the report, stated:

> *The global average temperature is much higher and is rising more rapidly than anything modern civilization has experienced, and this warming trend can only be explained by human activities.* (as cited in Yang, 2018, para. 7)

The USGCRP report carefully documents the ways in which global climate change is and will be impacting our health, weather, water and food supply, wildlife and biodiversity, oceans, and overall economy.

Human Health

One of the first human health impacts of global climate change comes as a result of rising temperatures. While a 1 °C (1.8 °F) increase in temperature may seem small, and while politicians may joke about welcoming global warming during cold spells, this figure represents an *average* global increase over the whole planet over an entire year. This means that localized heat waves and extreme heat events are already happening with increased frequency and deadly results. Global average temperatures are expected to continue to increase, further exacerbating the dangers of heat stress and other heat-related health conditions. The increased frequency and intensity of heat waves will also worsen air pollution conditions, including the formation of ground-level ozone and photochemical smog. In addition, as temperature and climate zones shift further away from the equator, tropical diseases like malaria and dengue fever will also reach into new regions and affect larger numbers of people. Overall, WHO (2018) estimates that rising global temperatures could result in as many as 250,000 premature deaths each year. In 2019 a report published in the *New England Journal of Medicine* called the WHO estimate too conservative and adjusted that figure to over 500,000 premature deaths every year (Haines & Ebi, 2019).

Severe and Extreme Weather

Carsten Schertzer/iStock/Getty Images Plus

The Thomas Fire in Santa Barbara, California, in 2017 was one of the largest and most destructive in the state's history. Catastrophic forest fires are one outcome of climate change in drier regions.

As the surface of the planet, the oceans, and the atmosphere warm, we can expect to see changes in rates of evaporation, cloud formation, and weather patterns. While no single weather event can be directly attributed to global climate change, scientists are now convinced that global warming has already begun to influence precipitation patterns and the frequency and intensity of severe storms. Some regions of the world are becoming wetter as a result of these changes, while others, like the western United States, are becoming drier. The regions becoming wetter are having to grapple with "too much of a good thing" as more frequent, sudden, and intense downpours create flooding conditions. In contrast, the drier regions are having to grapple with drought, reduced water supplies, and outbreaks of severe forest fires. It's no exaggeration to state that extreme weather has become the "new normal," and this has drawn the attention and concern of major global insurance companies. *Forbes* magazine recently reported that the cost of climate-related disasters has increased over 150% in the 21st century (McCarthy, 2018).

Water and Food Supply

As the weather changes, so will the reliability of water supply and our ability to grow food in certain locations. The USGCRP report mentioned at the start of this section estimates that higher temperatures in the U.S. Midwest will reduce corn and soybean yields by over 25% in the next few decades. Other research has established that global "wheat belts"—regions ideal for wheat production—are moving toward the poles (Jones, 2018). In Australia and South America, this means that the wheat belt is moving farther south, while in North America and Russia, it's shifting northward.

While this may sound relatively harmless, consider the fact that there is an entire infrastructure that has been developed around specific regions to support crop production in that location. Rail lines, roads, grain elevators, irrigation infrastructure, and warehouses would all have to be moved to keep up with shifting crop production zones. While such a move is conceivable in relatively wealthy countries like the United States and Australia, that's not the case in poorer regions of the world. Farmers in Africa, Latin America, and southern Asia are already suffering from climate-related crop losses and outright crop failure. Worsening agricultural conditions in these regions are contributing to poverty and an increase in the number of migrants and refugees fleeing these conditions. This has given rise to the notion of **climate refugees**. The World Bank (2018) estimates that climate change could soon cause over 140 million people to become climate refugees. Water shortages caused by shifting precipitation patterns and increased heat waves will only make this situation worse.

Wildlife and Biodiversity

A 2019 report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services warns that climate change could soon become the leading cause of species extinction and biodiversity loss (Díaz et al., 2019). This is because climate change—especially when combined with habitat destruction, pollution, and overexploitation—can rapidly modify the habitats and conditions that species have adapted to over long periods. A 2018 study published in the journal *Science* concluded that within a century climate change could result in many of the Earth's major ecosystems being "unrecognizable" (Nolan et al., 2018). For example, large areas of the Amazon rain forest could convert to savanna and grassland because of warmer temperatures and shifts in precipitation, no longer supporting the species that are adapted to living there.

The IPCC forecasts that approximately 30% of all land-based plant and animal species could be driven to extinction as a result of the most likely predicted increase in temperature. If actual warming is worse than that, this figure could increase to 70%. Biodiversity loss in the oceans could be as bad or even worse, as warming ocean waters and acidification make conditions uninhabitable for marine species. Climate change has already been implicated in the extinction of a number of amphibians, plants, insects, birds, and mammals, but the most significant impacts will begin to be felt over the next few decades. Unless global climate change and global warming are brought under control, they will be key drivers of the sixth great extinction.

Economy and Infrastructure

Nearly all the climate change impacts just discussed have direct and indirect impacts on our economy. More frequent and severe heat waves lower productivity and increase health care costs. Increased frequency and damage from severe weather and storms will raise insurance rates and require increased spending by governments on disaster relief and rebuilding. Lower crop productivity and water shortages increase food prices and require increased public investment in water management and distribution systems. In addition, we know that sea levels are rising worldwide as a result of the expansion of warmer ocean waters and the melting of glaciers and ice sheets. This has resulted in increased coastal flooding in cities around the world and will make the problem of climate refugees even worse.

View Pictures Ltd/SuperStock

A number of major cities are investing in flood control technology, such as these large barriers on the Thames River in London.

When sea level rise is combined with more severe hurricanes and storms, it becomes even more of a concern. This was demonstrated in New York City during Hurricane Sandy in 2012 and in the Carolinas during Hurricane Florence in 2018. Given the massive cleanup costs associated with coastal flooding, many cities are investing in coastal barriers and other flood control structures. However, these structures are expensive to build and are not always effective at preventing flooding. In addition, scientists are increasingly concerned that global warming could lead to the complete collapse of the Antarctic ice sheets and unleash as much as 4 meters (13 feet) of sea level rise. Such an outcome would overwhelm any flood control structures, displace tens of millions of people, and wipe some cities and coastal regions off the map. A 2017 report in the journal *Land Use Policy* estimates that rising sea levels could result in as many as 2 billion people being displaced by the year 2100 (Geisler & Currens, 2017).

A somewhat unexpected economic consequence of global climate change is that it is opening up the Arctic region at “the top of the world” to increased shipping, mineral exploration, and other development activities. Mariners have long dreamed of a “Northwest Passage” from Europe through the Arctic to Asia, but thick sea ice for much of the year has made this almost impossible for most ships. As Arctic sea ice becomes thinner and less widespread, there is growing interest in this possibility (Struzik, 2016). Likewise, a reduction in sea ice is making more of the Arctic region accessible for mineral exploration and development (Rosenthal, 2012). While both of these developments could have some positive economic benefits in the short term, they also open up environmentally sensitive Arctic regions to increased ship traffic, oil spills, and other forms of pollution. In addition, because parts of this region are not clearly the territory of one country, it increases the probability of international disputes over valuable minerals and shipping lanes.

This section has only reviewed *some* of the possible consequences and impacts of global climate change. Yet it reveals how climate change is already affecting many aspects of our lives and how these impacts are forecast to get much worse in the next few decades. Given the direct and indirect costs of climate change to our health, food and water supply, homes and cities, and livelihoods, as well as to other organisms and species that share the Earth with us, what can be done to address this issue? We turn to that question in the next section.

8.7 Addressing Global Climate Change

Before we get into the specifics of how we might address the challenge of global climate change, we should first acknowledge that there are a growing number of individuals asking if we are already too late. For example, environmental author and journalist Bill McKibben (2012) has written about what he calls "global warming's terrifying new math." By this McKibben is referring to the fact that over the period from 1800 to the present, human activities have resulted in the release of roughly 1,400 gigatons (1,400 billion metric tons) of carbon dioxide to the atmosphere. Those emissions are largely responsible for the already observed 1 °C global warming experienced over the past century. Climate scientists and world leaders are now focused on keeping any future warming below 2 °C (in other words, we are already halfway there). In order to do that, they estimate that we should release no more than an additional 500 billion metric tons of carbon dioxide over the remainder of this century.

The problem, according to McKibben, is that there are at least another 2,800 billion metric tons of carbon dioxide locked up in known remaining coal, oil, and natural gas deposits. Given that fossil fuel companies have a record of funding "climate science denial" organizations and lobbying politicians against any action on climate change, McKibben and others worry that we are likely on a path to realizing those levels of emissions. If that were to happen, the planet would be in for global warming of at least 6 °C (11 °F) with absolutely catastrophic consequences for human and natural systems worldwide. These worst-case scenarios are being talked about more frequently in the scientific and policy communities, and they have resulted in what some are calling "a kind of dark realism" (Mufson, 2018). This has led to greater emphasis on finding ways to adapt to what is increasingly perceived to be inevitable climate change.

Climate change adaptation can take many different forms. In the agricultural sector, adaptation means helping farmers shift to drought-resistant crops or crops better suited to new climate conditions. In terms of cities and infrastructure, adaptation means planning and building in ways that are more "climate-proof" than is currently the case. For example, when Hurricane Michael struck the Florida Panhandle in 2018, it destroyed all the homes along Mexico Beach except for one that was built to withstand hurricanes. Other adaptation strategies center on water management, fire prevention, and disease control, but all of them start with accepting the reality and severity of global climate change and preparing for the worst. (For information on your area, see the *Close to Home* feature.)

Close to Home: Adapting to Shifting Climates

Climate change adaptation is all about anticipating the shifts that accompany climate change. To help us visualize climate-related changes in the United States, researchers from the University of Maryland created a climate analogy map that predicts how specific locations might change by the year 2080 if we do not curb emissions. You can select a location, and the app will identify an analog city that best represents the future climate. Take a moment to explore the changes happening around the country and see if you can identify any major trends.

You might notice that several locations in the Northeast could begin to resemble locations in the southern and central United States. The western United States could start to resemble the Southwest, and the southern United States might start to look a lot like Mexico. On average, climates would shift by more than 965 kilometers (600 miles) with just a few degrees of warming, and many places could have a hard time adjusting.

Locations in the Northeast, for example, will likely experience some of the most dramatic temperature changes in the continental United States. Winters are expected to warm 3 times faster than summers, and ecosystems could be radically altered as a result. Many locations in the Southwest will need to cope with less rain and more frequent forest fires. Meanwhile, locations in the Northwest will grapple with irregular rainfall and flooding. Coastal locations will experience higher sea levels, more frequent hurricanes, and saltwater intrusion into freshwater sources. Most places are going to experience more extreme periods of hot weather. This will be a public health issue in places that are not used to the heat, and it will decrease economic productivity in southern locations that are already very hot.

robertharding/SuperStock

Beachside houses, such as these in Galveston, Texas, are at high risk during hurricanes, with only careful structural engineering giving homes a chance at survival.

With changes like these on the horizon, some cities are taking precautionary measures to become more climate resilient. New York created a task force to identify areas that are prone to flooding with sea level rise. Los Angeles is adding new infrastructure to capture rainwater. Cities like Oakland and St. Paul are rebuilding wetlands to provide flood control, and locations like Minneapolis and Chicago are adding green spaces to help manage the heat island effect.

With some of these challenges and solutions in mind, take a closer look at your hometown using the climate analogy map. If you would like to learn more about trends in your region, you can also explore the NOAA's Climate at a Glance tool. This online resource allows users to visualize several decades of temperature and precipitation data that is organized by state, county, and city. Based on what you can learn from these two sources, how will temperature and precipitation change in your area, and what specific concerns do you have for your community? Most importantly, what are some ways that your community might prepare so that it is ready for these changes? As you go forward, take time to appreciate the things that make your hometown special and start the conversation about climate resilience in your community.

While climate change adaptation will be important, there is still a need to focus on practices that can reduce or prevent greenhouse gas emissions in the first place. Those practices represent an approach known as **climate change mitigation**, and there are a number of ways that we can accomplish this.

Using Policy

Politically, many (but not all) world governments are now attempting to tackle the climate change challenge through the **Paris Agreement**. The Paris Agreement was signed in 2016 and commits participating countries to reduce greenhouse gas emissions according to formulas that take into consideration a country's historical emissions. The goal is to reduce greenhouse gas emissions enough to keep any global warming below 2 °C. At this point, however, countries participating in the Paris Agreement have only actually pledged to cut emissions by about one third of what is needed to limit warming to 2 °C, and these pledges are voluntary. To make matters worse, in June 2017 President Trump announced that the United States would withdraw from the agreement. Seeing that the United States is the number two emitter of greenhouse gases (after China), this decision has further called into question whether a global climate agreement can have enough of an impact in a short enough time period.

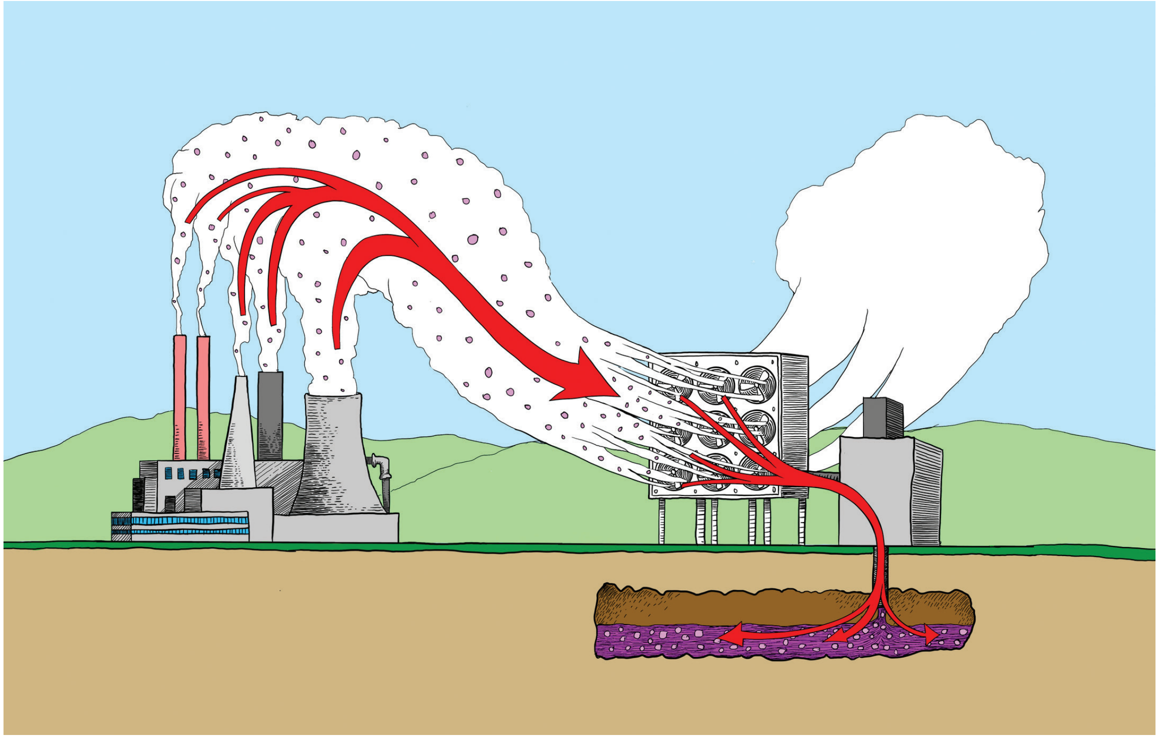
While the Trump administration has decided to turn its back on the challenge of global climate change, the same cannot be said for many state and local governments. For example, 10 states in the northeastern United States have formed the Regional Greenhouse Gas Initiative as a market-based program to reduce greenhouse gas emissions. California adopted a greenhouse gas cap-and-trade program in 2013 that allows polluting industries to buy and sell greenhouse gas emission permits from each other while gradually reducing overall emission levels. Other states are developing climate action plans, setting renewable energy targets, and promoting energy efficiency in homes and businesses to help reduce greenhouse gas emissions. Private companies and institutions such as colleges and universities are also taking steps to lower their greenhouse gas emissions. These companies and institutions are motivated both by a desire to do what they can to avoid climate change and by the financial savings that come from reducing energy use. This "no-regrets" or "win–win" approach to reducing greenhouse gas emissions could also apply at the national level, but it's more difficult to gain traction there due to opposition from fossil fuel industries.

Using Technology

Given the dangers associated with some of the worst predictions around global climate change, some scientists are not waiting for political action or economic incentives to have an impact on reducing emissions. These scientists are focused on technological approaches that either would pull or remove greenhouse gases from the atmosphere or would create conditions to offset or counter the warming caused by increased greenhouse gas concentrations. The first set of approaches are known broadly as *negative emissions technologies*, while the second set of approaches has been labeled *geoengineering*.

Negative Emissions Technologies

The most common **negative emissions technologies (NET)** approaches focus on removing carbon dioxide from the atmosphere in large enough quantities to impact greenhouse warming. This can be done by simply growing more trees (reforestation), since trees use CO_2 during photosynthesis and store that carbon in their tissue. Likewise, *bioenergy with carbon capture and sequestration (BECCS)* involves growing plants that suck up carbon dioxide and then burning those plants for energy in a way that captures CO_2 emissions.



IGphotography/iStock/Getty Images Plus

One NET approach involves walls of giant fans that suck in air to remove the CO_2 and store it underground.

The problem with both reforestation and BECCS is that in order to remove just one fourth of our annual CO_2 emissions, we would have to make use of approximately 40% of all global farmland, impacting food supply and prices. A different NET approach involves walls of giant fans that suck in air and remove the CO_2, although prototypes of this technology in Switzerland and Iceland have proved expensive. Despite these challenges, NET approaches are drawing increased attention, such as a 2019 National Academy of Sciences report that details the potential and limitations of these technologies (National Academies of Sciences, Engineering, and Medicine, 2019).

Learn More: NET Approaches

Download a free PDF of the 2019 National Academy of Sciences report on NET approaches at the following link:

- https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda

Geoengineering

Geoengineering involves deliberately trying to alter Earth's energy balance. For example, the 1991 eruption of Mount Pinatubo in the Philippines resulted in a massive injection of sulfur particles into the atmosphere. Sulfur particles reflect incoming sunlight, and in the months that followed the eruption, temperatures in the Northern Hemisphere actually dropped by about 0.6 °C (1 °F). One approach to geoengineering would therefore involve artificially injecting massive amounts of sulfur particles into the upper atmosphere. Another approach involves "fertilizing" regions of the ocean with iron in order to promote algae blooms. The algae would absorb carbon dioxide through photosynthesis and then sink to the bottom, where that carbon could be stored. Geoengineering, however, is risky and highly controversial. It involves actions on a global scale that could have serious unintended consequences. Nevertheless, given the seriousness of global climate change, some scientists argue that we need to keep researching it as a possibility.

Taking It One Step (or Wedge) at a Time

Because addressing global climate change can seem overwhelming, some scientists are using a concept known as **stabilization wedges**. The stabilization wedge approach basically involves taking our current greenhouse gas emissions and identifying ways to reduce those emissions one small piece, or wedge, at a time. These wedges include energy efficiency, a shift to more renewable energy, making vehicles more fuel efficient, and capturing and storing carbon using negative emissions technologies. When looked at this way, tackling greenhouse gas emissions and global warming seems a little less daunting. The key will be to move beyond the backward-looking and potentially paralyzing debates over whether climate change is happening (it is) and whether we are causing it (we are) and speed up the adoption of these wedge approaches.

Bringing It All Together

It's instructive to consider the question of why the world was able to so effectively respond to address the global challenge of stratospheric ozone depletion but has not been able to reach much consensus on the more pressing issue of global climate change. There appear to be at least three key answers to this question.

First, in the case of ozone depletion, there was only one class of chemicals (CFCs) responsible for the problem, and by the time the Montreal Protocol was being negotiated, effective substitutes were being developed to replace them. In contrast, global climate change is being caused by a wide variety of human actions, and the number of industries potentially impacted by climate change regulations is also far greater than was the case for ozone depletion. The fossil fuel industry, in particular, has waged a low-profile but highly effective campaign for decades to cast doubt on the scientific consensus surrounding climate change (Banerjee, Song, & Hasemyer, 2015; Frumhoff & Oreskes, 2015; Jerving, Jennings, Hirsch, & Rust, 2015; Union of Concerned Scientists, n.d.). As a result, public opinion has been split over the urgency of dealing with climate change, and the issue has become highly politicized.

A second reason for the different response to ozone depletion versus climate change has to do with the sense of immediacy and urgency of the problem. Media reports of ozone depletion and an ozone hole in the 1980s and 1990s focused on the risk of skin cancer and death. In contrast, while global climate change poses an even greater overall risk to humanity than ozone depletion, it is sometimes difficult for the average person to pinpoint how climate change might already be impacting him or her.

Finally, a scientific understanding and explanation for ozone depletion was easier to achieve because of the relatively limited scope of the problem and its causes. In contrast, the global climate system is far more complex, and predicting precisely how the climate will respond to increasing greenhouse gas concentrations in any one location is challenging.

In order to move beyond the political gridlock that is currently limiting our ability to respond effectively to global climate change, we need to go back to the concept of positive and normative claims. Climate scientists are growing increasingly frustrated with bogus arguments about climate change being some kind of "hoax" or "fake news." Scientific observations and reporting of rising greenhouse gas concentrations, increasing temperatures, rising sea levels, shrinking ice caps and ice sheets, retreating glaciers, and more severe weather are *not* fake news. Attributing those changes to human actions, in particular the burning of fossil fuels, is *not* part of some elaborate hoax designed to bring about the end of the free world and capitalism. Instead, the reality of a changing climate and the role of humans in that process are grounded in the *positive* and scientific approach that's focused on *how the world actually is*.

Once we acknowledge that reality, we can then shift to *normative* debates about what to do about the problem, when to take action, and who should pay for addressing this challenge. In order to do that, we need a scientifically literate (indeed, a "climate literate") public, and so we hope that this chapter has helped explain some of the major threats to sustaining our atmosphere and climate, as well as what we might do to respond to those threats.

Additional Resources

Air Pollution

The National Weather Service has on online Air Quality Index map that show what air-quality conditions are in your area.

- https://www.weather.gov/safety/airquality-aqindex

Smog City 2 is an online, interactive pollution simulator that allows you to manage air pollution conditions in a fictional city.

- http://www.smogcity2.org

Stratospheric Ozone Depletion

NASA has a couple of web pages that allow you to visualize how conditions in the ozone layer have changed over time.

- https://ozonewatch.gsfc.nasa.gov
- https://climate.nasa.gov/climate_resources/186/video-ozonewatch-2018

A recent NASA research study demonstrated that the phaseout of many ozone-depleting substances through the Montreal Protocol has definitely helped restore the ozone layer. However, soon after this report was released, evidence emerged that the use of these same ozone-depleting substances was on the increase again in parts of China. You can learn more about these good news/bad news stories at these sites.

- https://www.nasa.gov/feature/goddard/2018/nasa-study-first-direct-proof-of-ozone-hole-recovery-due-to-chemicals-ban
- https://e360.yale.edu/features/how-an-illicit-chemical-is-jeopardizing-recovery-of-the-ozone-layer-china

The Science of Global Climate Change

NASA has a number of great online resources that help explain the science of climate change, how climate has changed over time, what the impacts of climate change might be, and what some possible solutions are.

- https://climate.nasa.gov
- https://climate.nasa.gov/interactives/climate-time-machine
- https://earthobservatory.nasa.gov/world-of-change

Likewise, the NOAA also has excellent resources devoted to the science of climate change.

- https://www.climate.gov
- https://www.noaa.gov/education/resource-collections/climate-education-resources
- https://www.ncdc.noaa.gov/cag/national/time-series

The website Skeptical Science is “skeptical about global warming skepticism” and has a wealth of information on the basic science behind climate change.

- https://skepticalscience.com

Impacts of Global Climate Change

Few regions of the planet are being impacted as much by climate change as the Arctic. This fascinating photo essay by *The Washington Post* shows how lakes across the Arctic region are bubbling and changing in other ways as thawing permafrost releases carbon dioxide, methane, and other gases that have been trapped below them for thousands of years.

- https://www.washingtonpost.com/graphics/2018/national/arctic-lakes-are-bubbling-and-hissing-with-dangerous-greenhouse-gases

An interesting interactive feature in *The New York Times* allows you to examine how much hotter your hometown is today compared to when you were born.

- https://www.nytimes.com/interactive/2018/08/30/climate/how-much-hotter-is-your-hometown.html

A *Washington Post* photo essay documents how climate change is already disrupting lives across America.

- https://www.washingtonpost.com/graphics/2019/national/gone-in-a-generation

These two essays from *Yale Environment 360* show how climate change is already profoundly impacting Greenland and Antarctica.

- https://e360.yale.edu/features/in-greenlands-melting-ice-a-warning-on-hard-climate-choices
- https://e360.yale.edu/features/polar-warning-even-antarctica-coldest-region-is-starting-to-melt

Action on Global Climate Change

These two TED Talks by 16-year-old climate activist Greta Thunberg and climate scientist Katharine Hayhoe deliver a simple but powerful message on how and why to act on climate change.

- https://www.youtube.com/watch?v=H2QxFM9y0tY
- https://www.youtube.com/watch?v=-BvcToPZCLI

This *New York Times* interactive feature shows how the United States could do more to reduce greenhouse gas emissions if we did more of what some other countries are already doing.

- https://www.nytimes.com/interactive/2019/02/13/climate/cut-us-emissions-with-policies-from-other-countries.html

Geoengineering and negative emissions technologies are now being more openly discussed as a "last chance" strategy for dealing with the worst impacts of climate change. You can learn more about these approaches here.

- https://e360.yale.edu/features/geoengineer-the-planet-more-scientists-now-say-it-must-be-an-option
- https://e360.yale.edu/features/negative-emissions-is-it-feasible-to-remove-co2-from-the-air
- https://www.nap.edu/resource/25259/Negative%20Emissions%20Technologies.pdf

Key Terms

acid deposition Precipitation containing acid. Also known as *acid rain*.

acid rain See *acid deposition*.

albedo Degree of reflection.

cap and trade A regulatory approach that establishes a maximum level ("cap") for pollutant emissions and allows facilities to purchase ("trade") additional permits for emissions beyond the cap.

carbon dioxide (CO_2) A greenhouse gas that comes mainly from combustion of fossil fuels as well as from deforestation and other land-use changes.

carbon monoxide (CO) A primary pollutant. An invisible, odorless, tasteless gas that results from the incomplete combustion of carbon-based fuels, primarily from motor vehicle exhaust. A second major source of CO is firewood burning and forest fires.

chlorofluorocarbons (CFCs) An ozone-depleting substance typically used as a coolant.

Clean Air Act (CAA) A law passed in 1970 (and strengthened in 1977 and 1990) that sets air-quality standards for specific pollutants like carbon monoxide and nitrogen oxides and then imposes fines and penalizes violators of those standards.

climate Average temperature and precipitation patterns in a given area over a longer period.

climate change adaptation A response to global climate change that involves making changes and strategizing in preparation for a different climate.

climate change mitigation A response to global climate change that tries to limit or halt the effects of global climate change and often involves trying to reduce or prevent greenhouse gas emissions.

climate refugees People displaced due to global climate change.

convective circulation The circular motion of air that results as air warms and rises, cools and sinks, then warms and rises again.

criteria air pollutants The six air pollutants limited by the Clean Air Act: carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide.

energy balance When referring to the Earth, the equilibrium between incoming energy from the sun and outgoing energy as heat.

geoengineering An approach to climate change mitigation that involves trying to alter the Earth's energy balance.

global climate change A worldwide shift in climate (precipitation patterns, air currents, humidity, and other factors) due to the warming of the atmosphere and oceans.

greenhouse effect The process by which the Earth's atmosphere retains outgoing infrared (heat) energy and warms the planet.

greenhouse gas Any atmospheric gas that absorbs infrared radiation and contributes to the greenhouse effect.

halocarbon gas A greenhouse gas and ozone-depleting substance, including chlorofluorocarbons (CFCs).

lead (Pb) A primary pollutant. A metal, particulate air pollutant that can enter the atmosphere from combustion of leaded fuels as well as from waste incinerators, lead smelters, coal burning, mining, and battery manufacturing facilities.

methane (CH_4) A greenhouse gas that comes mainly from agricultural activities like rice farming and cattle production, as well as from leaks from natural gas pipelines and drilling facilities.

Montreal Protocol An agreement among 180 countries to address the issue of ozone depletion by phasing out chlorofluorocarbons.

negative emissions technologies (NET) Approaches to climate change mitigation that usually focus on removing carbon dioxide from the atmosphere.

nitrogen oxide (NO_x) A primary pollutant. Includes nitric oxide (NO) and nitrogen dioxide (NO_2). Most NO_x emissions come from internal combustion engines in vehicles, as well as from wood burning and forest fires. NO_2 is a reddish-brown gas that can cause lung irritation and respiratory disease; it can also react with water vapor to form a secondary pollutant known as nitric acid (HNO_3).

nitrous oxide (N_2O) A greenhouse gas that comes from fertilizer use and fossil fuel combustion.

ozone (O_3) A molecule made up of three oxygen atoms that is an air pollutant in the troposphere but absorbs UV radiation in the stratosphere.

ozone-depleting substances A class of chemicals that are known to destroy ozone.

ozone layer A region 18 to 26 kilometers (11 to 16 miles) above the Earth that contains most of the ozone in the stratosphere and that helps filter out harmful UV radiation before it strikes the Earth's surface.

Paris Agreement An international climate change agreement signed in 2016 that commits countries to reduce greenhouse gas emissions.

particulate matter (PM) A primary pollutant. Solid and liquid particles that are small and light enough to remain suspended in the air.

photochemical oxidant Ozone pollution.

photochemical smog A form of air pollution that contains photochemical oxidants such as ozone.

primary air pollutants Pollutants that are emitted directly into the atmosphere.

secondary air pollutants Pollutants that are formed through chemical reactions in the atmosphere between primary pollutants and other substances.

sinks Natural processes that absorb and store a chemical such as carbon.

stabilization wedges An approach to climate change mitigation that identifies ways to reduce greenhouse gas emissions one step (wedge) at a time.

stratosphere The region of the atmosphere above the troposphere that ranges from 18 to 50 kilometers (11 to 31 miles) above the surface of the Earth.

stratospheric ozone depletion The reduction of ozone in the stratosphere.

sulfur dioxide (SO_2) A primary pollutant. Results from the combustion of fuels that contain sulfur, primarily from burning coal in power plants. SO_2 can react in the atmosphere to form a secondary pollutant known as sulfuric acid (H_2SO_4).

troposphere The lowest region of the atmosphere; it extends from the surface to 8 to 18 kilometers (5 to 11 miles) above the Earth.

volatile organic compounds (VOCs) A range of chemical compounds that originate from both natural sources and human activities and that can easily become a vapor or gas.

weather Day-to-day changes in temperature, atmospheric pressure, precipitation, humidity, and wind.