CHAPTER SIX

Changes in the Climate System

Scientific understanding of the factors and processes that govern the evolution of Earth's climate has increased markedly over the past several decades, as has the ability to simulate and project future changes in the climate system. As noted in Chapter 2, this knowledge has been regularly assessed, synthesized, and summarized by the Intergovernmental Panel on Climate Change (IPCC), the U.S. Global Climate Research Program (USGCRP, referred to as the U.S. Climate Change Science Program from 2000 to 2008), and other groups to provide a thorough and detailed description of what is known about past, present, and projected future changes in climate and related human and environmental systems. This chapter provides an updated overview of the current state of knowledge about the climate system, followed by a list of some of the key scientific advances needed to further improve our understanding.

To help frame the sections that follow, it is useful to consider some questions that decision makers are asking or will be asking about changes in the climate system:

- How are temperature and other aspects of climate changing?
- How do we know that humans are responsible for these changes?
- How will temperature, precipitation, severe weather, and other aspects of climate change in my city/state/region over the next several decades?
- Will these changes be steady and gradual, or abrupt?
- Will seasonal and interannual climate variations, like El Niño events, continue the same way or will they be different?
- Why is there so much uncertainty about future changes?

This chapter attempts to answer these questions or explain what additional research would be needed to answer them. The chapters that follow focus on the impacts of climate change on a range of human and environmental systems, the role of these systems in driving climate change, and the state of scientific knowledge regarding actions that could potentially be taken to adapt to or limit the magnitude of climate change in those systems. All of the chapters in Part II follow a similar structure and are more detailed and extensively referenced than the concise overview of climate change science found in Chapter 2. However, these chapters represent only highlights of a broad and extensive collection of scientific research; readers desiring further detail are encouraged to consult other recent assessment reports and the primary literature.

FACTORS INFLUENCING EARTH'S CLIMATE

The Greenhouse Effect

The Earth's physical climate system, which includes the atmosphere, oceans, cryosphere, and land surface, is complex and constantly evolving. Nevertheless, the laws of physics, chemistry, and biology ultimately govern the system and can be used to understand how and why climate varies from place to place and over time. For example, the energy balance of the Earth as a whole is determined by the difference between incoming and outgoing energies at the top of the atmosphere. The only significant incoming energy is radiation from the sun, which is concentrated at short wavelengths (visible and ultraviolet light), while the outgoing energy includes both infrared (long-wavelength) radiation emitted by the Earth and the portion of incoming solar radiation (about 30 percent on average) that is reflected back to space by clouds, small particles in the atmosphere, and the Earth's surface. If the outgoing energy is slightly lower than the incoming energy for a period of time, then the climate system as a whole will warm until the outgoing radiation from the Earth balances the incoming radiation from the sun.

The temperature of the Earth's surface and lower atmosphere depends on a broader range of factors, but the transfer of radiation again plays an important role, as does the composition of the atmosphere itself. Nitrogen (N_2) and oxygen (O_2) make up most of the atmosphere, but these gases have almost no effect on either the incoming radiation from the sun or the outgoing radiation emitted by the Earth's surface. Certain other gases, however, absorb and reemit the infrared radiation emitted by the surface, effectively trapping heat in the lower atmosphere and keeping the Earth's surface much warmer—roughly 59°F (33°C) warmer—than it would be if greenhouse gases were not present.[1] This is called the *greenhouse effect*, and the gases that cause it—including water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—are called greenhouse gases (GHGs). GHGs only constitute a small fraction of the Earth's atmosphere, but even relatively small increases in the amount of these gases in the atmosphere can amplify the natural greenhouse effect, warming the Earth's surface (see Figure 2.1).

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[1] This difference includes the greenhouse effect associated with clouds, which are composed of water droplets, but it assumes that the total reflectivity of the Earth—including the reflection by clouds—does not change.

Carbon Dioxide

The important role played by CO_2 in the Earth's energy balance has been appreciated since the late 19th century, when Swedish scientist Svante Arrhenius first proposed a link between CO_2 levels and temperature. At that time, humans were only beginning to burn fossil fuels—which include coal, oil, and natural gas—on a wide scale for energy. The combustion of these fuels, or any material of organic origin, yields mostly CO_2 and water vapor, but also small amounts of other by-products, such as soot, carbon monoxide, sulfur dioxide, and nitrogen oxides. All of these substances occur naturally in the atmosphere, and natural fluxes of water and CO_2 between the atmosphere, oceans, and land surface play a critical role in both the physical climate system and the Earth's biosphere. However, unlike water vapor molecules, which typically remain in the lower atmosphere for only a few days before they are returned to the surface in the form of precipitation, CO_2 molecules are only exchanged slowly with the surface. The excess CO_2 emitted by fossil fuel burning and other human activities will thus remain in the atmosphere for many centuries before it can be removed by natural processes (Solomon et al., 2009).

A number of agencies and groups around the world, including the Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory and the International Energy Agency, produce estimates of how much CO_2 is released to the atmosphere every year by human activities. The most recent available estimates indicate that, in 2008, human activities released over 36 Gt (gigatons, or billion metric tons) of CO_2 into the atmosphere—including 30.6 ± 1.7 Gt from fossil fuel burning, plus an additional 4.4 ± 2.6 Gt from land use changes and 1.3 ± 0.1 Gt from cement production (Le Quéré et al., 2009). Emissions from fossil fuels have increased sharply over the last two decades, rising 41 percent since 1990 (Figure 6.1). CO_2 emissions due to land use change—which are dominated by tropical deforestation—are estimated based on a variety of methods and data sources, and the resulting estimates are both more uncertain and more variable from year-to-year than fossil fuel emissions. Over the past decade (2000–2008), Le Quéré et al. (2009) estimate that land use changes released 5.1 ± 2.6 Gt of CO_2 each year, while fossil fuel burning and cement production together released on average 28.2 ± 1.7 Gt of CO_2 per year.

Up until the 1950s, most scientists thought the world's oceans would simply absorb most of the excess CO_2 released by human activities. Then, in a series of papers in the late 1950s (e.g., Revelle and Suess, 1957), American oceanographer Roger Revelle and several collaborators hypothesized that the world's oceans could not absorb all the excess CO_2 being released from fossil fuel burning. To test this hypothesis, Revelle's colleague C. D. Keeling began collecting canisters of air at the Mauna Loa Observatory
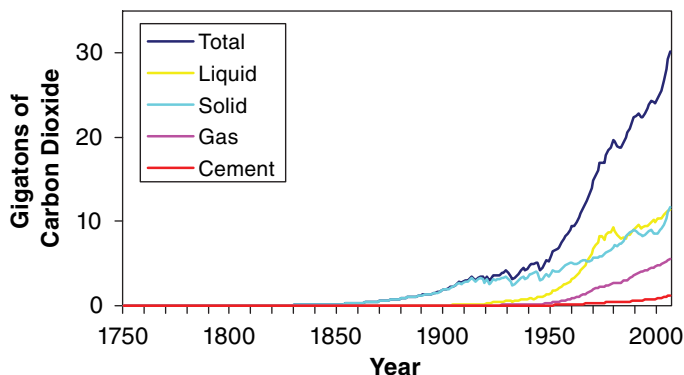
FIGURE 6.1 Estimated global CO_2 emissions from fossil fuel sources, in gigatons (or billion metric tons). Based on data from Boden et al. (2009; available at *http://cdiac.ornl.gov/trends/emis/tre_glob.html*).

in Hawaii, far away from major industrial and population centers, and analyzing the composition of these samples to determine whether CO_2 levels in the atmosphere were increasing. Similar in situ measurements continue to this day at Mauna Loa as well as at many other sites around the world. The resulting high-resolution, well-calibrated, 50-year-plus time series of highly accurate and precise atmospheric CO_2 measurements (Figure 6.2), commonly referred to as the Keeling curve, is both a major scientific achievement and a key data set for understanding climate change.

The Keeling curve shows that atmospheric CO_2 levels have risen by more than 20 percent since 1958; as of January 2010, they stood at roughly 388 ppm, rising at an average annual rate of almost 2.0 ppm per year over the past decade (Blasing, 2008; Tans, 2010). When multiplied by the mass of the Earth's atmosphere, this increase corresponds to 15.0 ± 0.1 Gt CO_2 added to the atmosphere each year, or roughly 45 percent of the excess CO_2 released by human activities over the last decade. The remaining 55 percent is absorbed by the oceans and the land surface. The size of these CO_2 "sinks" is estimated via both modeling and direct observations of CO_2 uptake in the oceans and on land. These estimates indicate that the oceans absorbed on average 8.4 ± 1.5 Gt CO_2 annually over the last decade (or 26 percent of human emissions), while the land surface took up 11.0 ± 3.3 Gt per year (29 percent), with a small residual of 0.3 Gt (Le Quéré et al., 2009).

A careful examination of the Keeling curve reveals that atmospheric CO_2 concentrations are currently increasing twice as fast as they did during the first decade of the record (compare the slope of the black line in Figure 6.2). This acceleration in the rate of CO_2 rise can be attributed in part to the increases in CO_2 emissions due to increasing
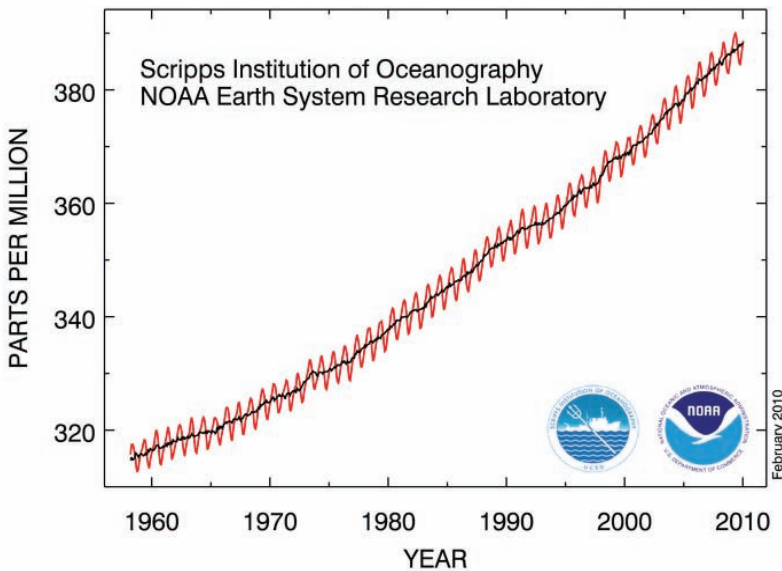
FIGURE 6.2 Atmospheric CO_2 concentrations (in parts per million [ppm]) at Mauna Loa Observatory in Hawaii. The red curve, which represents the monthly averaged data, includes a seasonal cycle associated with regular changes in the photosynthetic activity in plants, which are more widespread in the Northern Hemisphere. The black curve, which represents the monthly averaged data with the seasonal cycle removed, shows a clear upward trend. SOURCE: Tans (2010; available at *http://www.esrl.noaa. gov/gmd/ccgg/trends/*).

energy use and development worldwide (as indicated in Figure 6.1). However, recent studies suggest that the rate at which CO_2 is removed from the atmosphere by ocean and land sinks may also be declining (Canadell et al., 2007; Khatiwala et al., 2009). The reasons for this decline are not well understood, but, if it continues, atmospheric CO_2 concentrations would rise even more sharply, even if global CO_2 emissions remain the same. Improving our understanding and estimates of current and projected future fluxes of CO_2 to and from the Earth's surface, both over the oceans and on land, is a key research need (research needs are discussed at the end of the chapter).

To determine how CO_2 levels varied prior to direct atmospheric measurements, scientists have studied the composition of air bubbles trapped in ice cores extracted from the Greenland and Antarctic ice sheets. These remarkable data, though not as accurate and precise as the Keeling curve, show that CO_2 levels were relatively constant for thousands of years preceding the Industrial Revolution, varying in a narrow band between 265 and 280 ppm, before rising sharply starting in the late 19th century (Figure 6.3). The current CO_2 level of 388 ppm is thus almost 40 percent higher
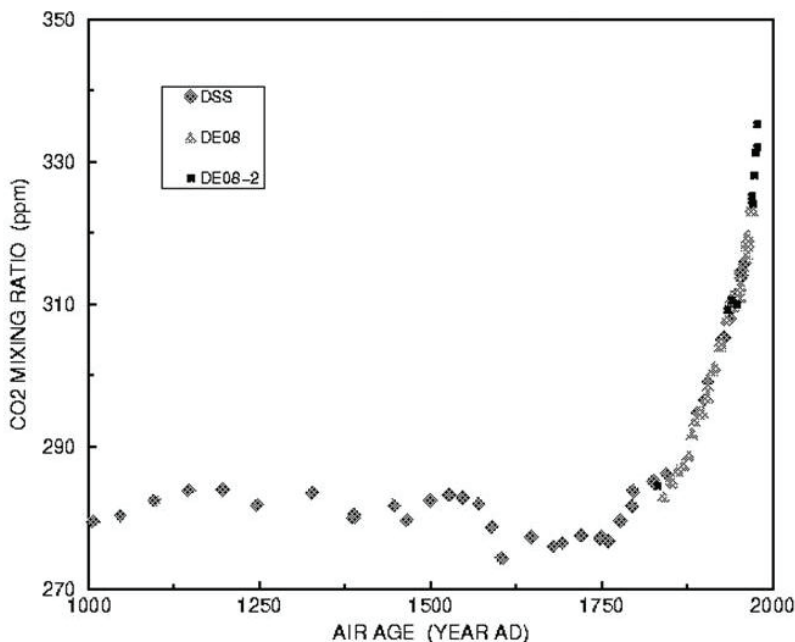
FIGURE 6.3 CO_2 variations during the last 1,000 years, in parts per million (ppm), obtained from analysis of air bubbles trapped in an ice core extracted from Law Dome in Antarctica. The data show a sharp rise in atmospheric CO_2 starting in the late 19th century, coincident with the sharp rise in CO_2 emissions illustrated in Figure 6.1. Similar data from other ice cores indicate that CO_2 levels remained between 260 and 285 ppm for the last 10,000 years. SOURCE: Etheridge et al. (1996).

than preindustrial conditions (usually taken as 280 ppm). As discussed in further detail in the next section, data from even longer ice cores extracted from the hearts of the Greenland and Antarctic ice sheets—the bottoms of which contain ice that was formed hundreds of thousands of years ago—indicate that the current CO_2 levels are higher than they have been for at least 800,000 years.

Collectively, the in situ measurements of CO_2 over the past several decades, ice core measurements showing a sharp rise in CO_2 since the Industrial Revolution, and detailed estimates of CO_2 sources and sinks provide compelling evidence that CO_2 levels are increasing as a result of human activities. There is, however, an additional piece of evidence that makes the human origin of elevated CO_2 virtually certain: measurements of the isotopic abundances of the CO_2 molecules in the atmosphere—a chemical property that varies depending on the source of the CO_2—indicate that most of the excess CO_2 in the atmosphere originated from sources that are millions of years old. The only source of such large amounts of "fossil" carbon are coal, oil, and natural gas (Keeling et al., 2005).

Climate Forcing

Changes in the radiative balance of the Earth—including the enhanced greenhouse effect associated with rising atmospheric CO_2 concentrations—are referred to as climate *forcings* (NRC, 2005d). Climate forcings are estimated by performing detailed calculations of how the presence of a forcing agent, such as excess CO_2 from human activities, affects the transfer of radiation through the Earth's atmosphere.[2] Climate forcings are typically expressed in Watts per square meter (W/m^2, or energy per unit area), with positive forcings representing warming, and are typically reported as the change in forcing since the start of the Industrial Revolution (usually taken to be the year 1750). Figure 6.4 provides a graphical depiction of the estimated globally averaged strength of the most important forcing agents for recent climate change. Each of these forcing agents are discussed below.

Well-Mixed Greenhouse Gases

Carbon dioxide (*CO_2*). The CO_2 emitted by human activities is the largest single climate forcing agent, accounting for more than half of the total positive forcing since 1750 (see Figure 6.4). As of the end of 2005, the forcing associated with human-induced atmospheric CO_2 increases stood at 1.66 ± 0.17 W/m^2 (Forster et al., 2007). This number may seem small relative to the total energy received by the Earth from the sun (which averages 342 W/m^2, of which 237 W/m^2 is absorbed by the Earth system, after accounting for reflection of 30 percent of the solar energy back to space). When multiplied by the surface area of the Earth, however, the CO_2 forcing is roughly 850 terawatts, which is more than 50 times the total power consumed by all human activities.

Human activities have also led to increases in the concentrations of a number of other "well-mixed" GHGs—those that are relatively evenly distributed because their molecules remain in the atmosphere for at least several years on average. Many of these gases are much more potent warming agents, on a molecule-for-molecule basis, than CO_2, so even small changes in their concentrations can have a substantial influence. Collectively, they produce an additional positive forcing (warming) of 1.0 ± 0.1 W/m^2, for a total well-mixed GHG-induced forcing (including CO_2) of 2.63 ± 0.26 W/m^2

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[2] As discussed in NRC (2005e): "Radiative forcing traditionally has been defined as the instantaneous change in energy flux at the tropopause resulting from a change in a component external to the climate system. Many current applications [including the radiative forcing values discussed in this chapter] use an 'adjusted' radiative forcing in which the stratosphere is allowed to relax to thermal steady state, thus focusing on the energy imbalance in the Earth and troposphere system, which is most relevant to surface temperature change."
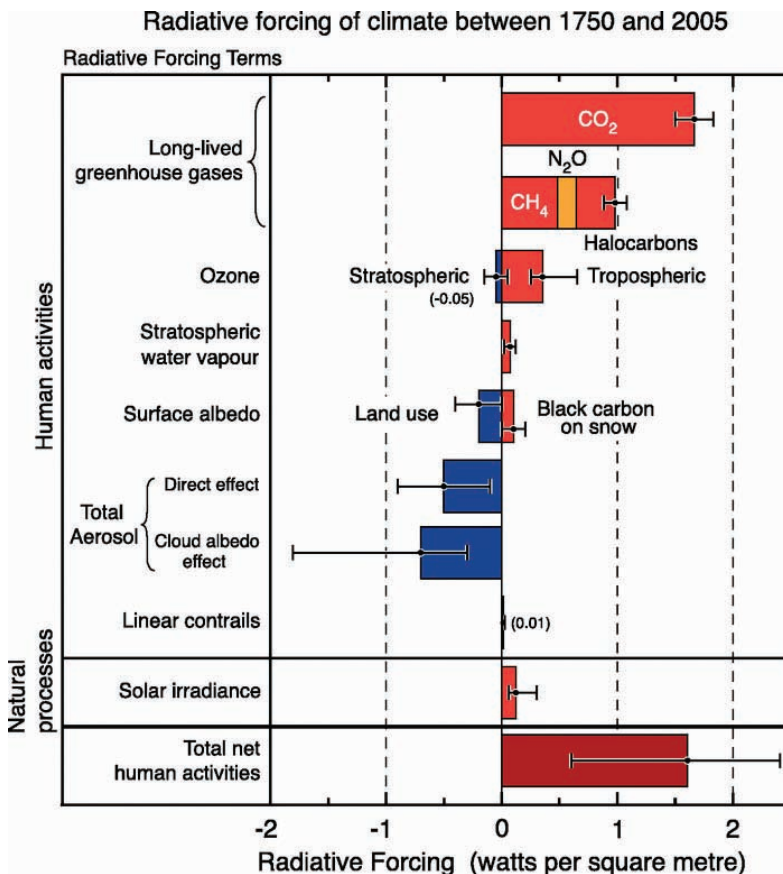
FIGURE 6.4 Radiative forcing of climate between 1750 and 2005 due to both human activities and natural processes, expressed in Watts per square meter (energy per unit area). Positive values correspond to warming. See text for details. SOURCE: Forster et al. (2007).

(Forster et al., 2007) (see Figure 6.4). Forcing estimates for all of the well-mixed GHGs are quite accurate because we have precise measurements of their concentrations, their influence on the transfer of radiation through the atmosphere is well understood, and they become relatively evenly distributed across the global atmosphere within a year or so of being emitted.

Methane (CH_4). Methane is produced from a wide range of human activities, including natural gas management, fossil fuel and biomass burning, animal husbandry, rice cultivation, and waste management (Houweling et al., 2006). Natural sources of CH_4—which are smaller than human sources—include wetlands and termites, and both of
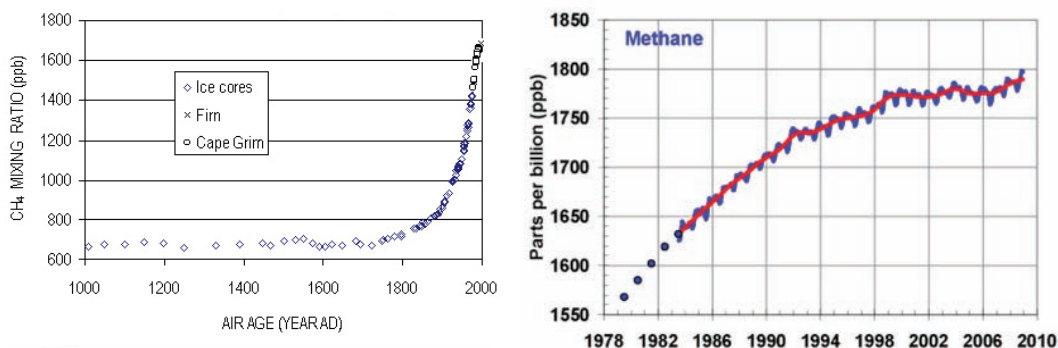
FIGURE 6.5 Atmospheric CH_4 concentrations in parts per billion (ppb), (left) during the past millennium, as measured in Antarctic ice cores, and (right) since 1979, based on direct atmospheric measurements. SOURCES: Etheridge et al. (2002) and NOAA/ESRL (2009).

these sources are actually influenced to some degree by changes in land use. Recent measurements have suggested that plants and crops may also emit trace amounts of CH_4 (Keppler et al., 2006), although the size of this source has been questioned (Dueck et al., 2007).

The atmospheric concentration of CH_4 rose sharply through the late 1970s before starting to level off, ultimately reaching a relatively steady concentration of around 1775 ppb—which is more than two-and-a-half times its average preindustrial concentration—from 1999 to 2006 (Figure 6.5). There have been several theories proposed for the apparent leveling off of CH_4 concentrations, including a decline in industrial emissions during the 1990s and a slowdown of natural wetland-related emissions (Dlugokencky et al., 2003). As discussed at the end of the chapter, there are also concerns that warming temperatures could lead to renewed rise in CH_4 levels as a result of melting permafrost across the Arctic (Schuur et al., 2009) or, less likely, the destabilization of methane hydrates[3] on the seafloor (Archer and Buffet, 2005; Overpeck and Cole, 2006). The causes of the recent uptick in concentrations in 2007 and 2008 are currently being studied (Dlugokencky et al., 2009).

Unlike CO_2, which is only removed slowly from the atmosphere by processes at the land surface, the atmospheric concentration of CH_4 is limited mainly by a chemical reaction in the atmosphere that yields CO_2 and water vapor. As a result, molecules of CH_4 spend on average less than 10 years in the atmosphere. However, CH_4 is a much

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[3] Methane hydrates are crystalline structures composed of methane and water molecules that can be found in significant quantities in sediments on the ocean floor.
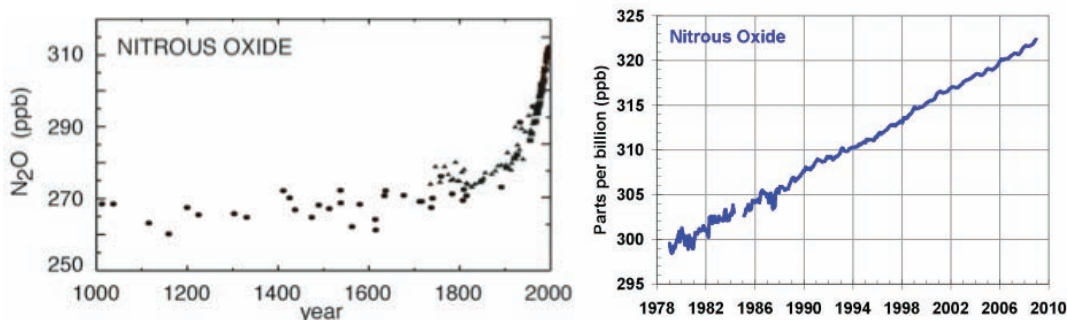
FIGURE 6.6 N_2O concentrations in the atmosphere, in parts per billion (ppb), (left) during the last millennium, and (right) since 1979. SOURCES: Etheridge et al. (1996) and NOAA/ESRL (2009).

more potent warming agent, on a molecule-for-molecule basis,[4] than CO_2, and its relative concentration in the atmosphere has risen by almost four times as much as CO_2. Hence, the increases in CH_4 since 1750 are associated with a climate forcing of roughly 0.48 ± 0.05 W/m^2 (Forster et al., 2007), or around 18 percent of the total forcing by well-mixed GHGs.

Nitrous oxide (N_2O). Concentrations of nitrous oxide in the atmosphere have increased around 15 percent since 1750, primarily as a result of agricultural activities (especially the application of chemical fertilizers) but also as a by-product of fossil fuel combustion and certain industrial process. The average atmospheric concentration of N_2O continues to grow at a steady rate of around 0.8 ppb per year and, as of the end of 2008, stood at just over 322 ppb (Figure 6.6) (see also NASA, 2008). N_2O is an extremely potent warming agent—more than 300 times as potent as CO_2 on a molecule-by-molecule basis—and its molecules remain in the atmosphere more than 100 years on average. Thus, even though N_2O concentrations have not increased nearly as much since 1750 as CH_4 or CO_2, N_2O still contributes a climate forcing of 0.16 ± 0.02 W/m^2 (Forster et al., 2007), or around 6 percent of total well-mixed GHG forcing. N_2O and its decomposition in the atmosphere also have a number of other environmental effects—for example, N_2O is now the most important stratospheric ozone-depleting substance being emitted by human activities (Ravishankara et al., 2009).

Halogenated gases. Over a dozen halogenated gases, a category that includes ozone-depleting substances such as chlorofluorocarbons (CFCs), hydrofluorocarbons, per-

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[4] The relative (molecule-by-molecule) radiative forcing of a GHG over a particular time scale (usually taken as 100 years), compared to carbon dioxide, is sometimes expressed as the global warming potential of the gas. Another common comparative metric is carbon dioxide equivalent (CO_2-eq), which describes the equivalent amount of carbon dioxide that would produce the same forcing.

fluorocarbons, and sulfur hexafluoride, also contribute to the positive climate forcing associated with well-mixed GHGs. Although relatively rare—their concentrations are typically measured in parts per trillion—many of the halogenated gases have very long residence times in the atmosphere and are extremely potent forcing agents on a molecule-by-molecule basis (Ravishankara et al., 1993). Collectively they contribute an additional 0.33 ± 0.03 W/m^2 of climate forcing. Most halogenated gases do not have any natural sources (see, e.g., Frische et al., 2006) but rather arise from a variety of industrial activities. Emissions of many of these ozone-depleting compounds have declined sharply over the past 15 years because of the Montreal Protocol (see below). As a result, their atmospheric concentrations, and hence climate forcing, are now declining slightly each year as they are slowly removed from the atmosphere by natural processes (Figure 6.7) (NASA, 2008). It has been estimated that the forcing associated with halogenated gases would be 0.2 W/m^2 higher than it is today if emissions reductions due to the Montreal Protocol had not taken place (Velders et al., 2007; see also Chapter 17).

Other Greenhouse Gases

Ozone (O_3). Ozone plays a number of important roles in the atmosphere, depending on location, and its concentration varies substantially, both vertically and horizontally. The highest concentrations of ozone are found in the stratosphere—the layer of the atmosphere extending from roughly 10 to 32 miles (15 to 50 km) in height (Figure 6.8)—where it is produced naturally by the dissociation of oxygen molecules by ultraviolet light. This chemical reaction, along with the photodissociation of ozone itself, plays the beneficial role of absorbing the vast majority of incoming ultraviolet radiation, which is harmful to most forms of life, before it reaches the Earth's surface. Levels of ozone in the stratosphere have been declining over the past several decades, especially over Antarctica. Scientific research has definitively shown that CFCs, along with a few other related man-made halogenated gases (see above), are responsible for these ozone losses in the stratosphere; thus, halogenated gases contribute to both global warming and stratospheric ozone depletion. The Montreal Protocol, which was originally signed in 1987 and has now been revised several times and ratified by 196 countries, has resulted in a rapid phase-out of these gases (see Figure 6.7). Recent evidence suggests that ozone levels in the stratosphere are starting to recover as a result, although it may be several more decades before the ozone layer recovers completely (CCSP, 2008a).

Near the Earth's surface, ozone is considered a pollutant, causing damage to plants and animals, including humans, and it is one of the main components of smog (see Chapter 11). Most surface ozone is formed primarily when sunlight strikes air that
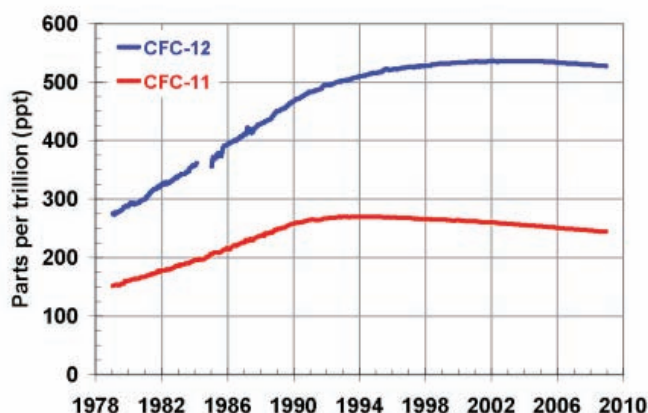
FIGURE 6.7 Atmospheric concentrations of the two halogenated gases with the largest individual climate forcings, CFC-11 and CFC-12, from 1979 to 2008. The Montreal Protocol limited the production of these and other compounds, and so their atmospheric concentrations are now slowly declining. SOURCE: NOAA/ESRL (2009).

contains nitrogen oxides (NO_x) in combination with carbon monoxide (CO) or certain volatile organic compounds (VOCs). All of these substances have natural sources, but their concentrations have increased as a result of human activities. Much of the NO_x and CO in the troposphere comes from man-made sources that involve burning, including automobile exhaust and power plants, while sources of VOCs include vegetation, automobiles, and certain industrial activities.

Ozone is also found in the upper troposphere, where its sources include local formation, horizontal and vertical mixing processes, and downward transport from the stratosphere. In general, tropospheric ozone levels show a lot of variability in both space and time, and there are only a few locations with long-term records, so it is difficult to estimate long-term ozone trends. Observational evidence to date shows increases in ozone in various parts of the world (e.g., Cooper et al., 2010). Models that include explicit representations of atmospheric chemistry and transport have also been used to estimate long-term ozone trends. These models, which are generally able to simulate observed ozone changes, indicate that tropospheric ozone levels have increased appreciably during the 20th century (Forster et al., 2007).

In addition to its role in near-surface air pollution and absorbing ultraviolet radiation in the stratosphere, ozone is a GHG, and so changes in its concentration yield a climate forcing. The losses of ozone in the stratosphere are estimated to yield a small negative forcing (cooling) of -0.05 ± 0.10 W/m^2, while increases in tropospheric ozone, which
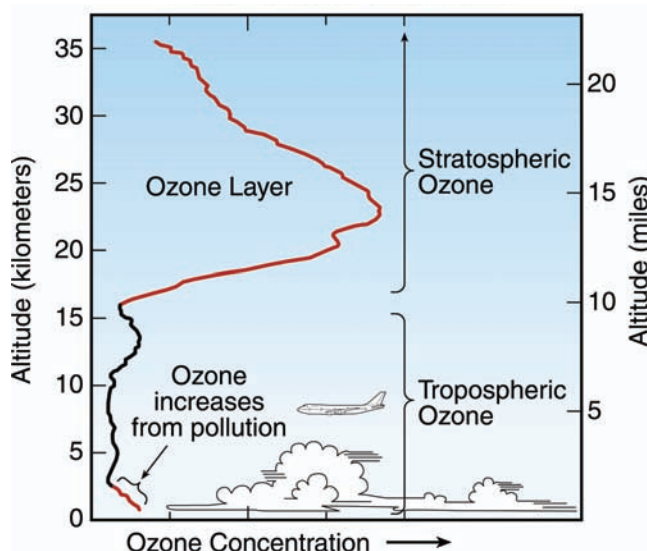
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FIGURE 6.8 The vertical distribution of ozone with height, showing the protective layer of ultraviolet-absorbing ozone in the stratosphere, the harmful ozone (smog) near the Earth's surface, and the lesser—but still important—amounts of ozone in the upper troposphere. SOURCE: UNEP et al. (1994).

are comparatively larger, are estimated to yield a positive forcing of between 0.25 and 0.65 W/m^2, with a best estimate of 0.35 W/m^2 (Forster et al., 2007) (see Figure 6.4). Thus, in total, the changes in atmospheric ozone are responsible for a positive forcing that is on par with the halogenated gases and possibly as large as or slightly larger than the forcing associated with CH_4. However, the exact ozone forcing is more uncertain than for the well-mixed GHGs.

Water vapor (*H_2O*). Water vapor is technically the most abundant GHG and also the most important in terms of its contribution to the *natural* greenhouse effect (see Figure 2.1). A number of human activities (primarily agricultural irrigation but also through cooling towers, aircraft exhaust, and other sources) can influence local water vapor levels. However, on a global basis the concentration of water vapor in the lower atmosphere is controlled by the rate of evaporation and precipitation, which are processes that occur on a relatively fast time scale and are much more strongly influenced by changes in atmospheric temperature and circulation than by human activities directly. Thus, water vapor is usually considered to be part of the climate system—and indeed, it is involved in a number of important climate feedback processes, as described below—rather than a climate forcing agent.

In the stratosphere, on the other hand, water vapor is relatively rare and somewhat isolated from the hydrological cycle in the lower atmosphere. Processes that influence water vapor concentrations at these high altitudes can thus lead to a small but discernible climate forcing. The largest such forcing is associated with the oxidation of CH_4 into water vapor and CO_2: as CH_4 concentrations have increased, so has this source of water vapor in the stratosphere, leading to a small positive climate forcing estimated to be 0.05 ± 0.05 W/m^2 (Hansen et al., 2005).[5] Recent satellite-based observations reveal that stratospheric water vapor levels have actually declined since 2000 (Solomon et al., 2010); the causes and possible implications of this decline are still being studied.

Other Climate Forcing Agents

Aerosols. Small liquid or solid particles suspended in the atmosphere—aerosols—can be composed of many different chemicals, come from many different sources (including both natural sources and human activities), and have a wide range of effects. Fossil fuel burning, industrial activities, land use change, and other human activities have generally increased the number of aerosol particles in the atmosphere, especially over and downwind of industrialized counties. The net climate forcing associated with aerosols is estimated to be -1.2 W/m^2 (Forster et al., 2007; see also Murphy et al., 2009), which offsets roughly one-third of the total positive forcing associated with human emissions of GHGs (see Figure 6.4). However, the forcing associated with aerosols is more uncertain than the forcing associated with GHGs, in part because the global distribution and composition of aerosols are not very well known and in part because of the diversity and complexity of aerosol radiative effects.

Two separate types of effects contribute to the net cooling associated with aerosols: (1) a "direct effect," which occurs because most aerosols scatter a portion of the incoming sunlight that strikes them back to space, and (2) "indirect effects," which arise because aerosols play an important role in the formation and properties of cloud droplets, and on average the increasing number of aerosols have caused clouds to reflect more sunlight back to space. Certain kinds of aerosols, including dust particles

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[5] Exhaust from jet aircraft also adds water vapor to the stratosphere, which can both directly contribute to the greenhouse effect and also form linear contrails, which tend to warm the Earth slightly. While contrails were once thought to potentially contribute a significant climate forcing, more recent estimates—including some based on measurements taken during the days following the September 11 attacks, when air travel over North America was sharply curtailed—show that aircraft exhaust has only a small effect on climate forcing, although contrails do appear to have a discernible effect on regional day-night temperature differences (Travis et al., 2002).

and black carbon (soot), absorb both incoming solar energy and the outgoing infrared energy emitted by the Earth. These aerosols tend to warm the atmosphere, offsetting some (but not all) of the cooling associated with the direct and indirect effects. Black carbon particles that settle on snow and ice surfaces can also accelerate melting; however, this positive forcing is typically included in estimates of the forcing associated with land use change, which is discussed below.

It is worth noting the sources of a few key types of aerosols to illustrate their diversity: Dust and some organic aerosols arise from natural processes, but some human activities such as land use change also lead to changes in the abundance of these species. Black carbon particles are produced from the burning of both fossil fuels and vegetation. Sulfate (SO_4) aerosols—which are a major contributor to the aerosol direct and indirect effects—have three notable sources: fossil fuel burning, marine phytoplankton, and volcanoes. The composition and size of each of these aerosol species affect how they absorb or scatter radiation, how much water vapor they absorb, how effectively they act to form cloud droplets, and how long they reside in the atmosphere—although in general most aerosols only remain in the atmosphere for a few weeks on average.

In addition to their role in global climate forcing, aerosols also have a number of other important environmental effects. The same industrial emissions that give rise to SO_4 aerosols also contribute to acid rain, which has a major detrimental effect on certain ecosystems. One of the major objectives—and successes—of the 1990 Clean Air Act (P.L. 101-549) was to reduce the amount of sulfur emissions in the United States. Similar laws in Europe have also been successful in reducing SO_4 aerosol concentrations (Saltman et al., 2005). The relationship between aerosols and cloud formation also means that changes in aerosols play an important role in modulating precipitation processes (see Chapters 8 and 15). Also, many aerosols are associated with negative impacts on public health, as discussed in further detail in Chapter 11.

Finally, aerosol emissions represent an important dilemma facing policy makers trying to limit the magnitude of future climate change: If aerosol emissions are reduced for health reasons, or as a result of actions taken to reduce GHG emissions, the net negative climate forcing associated with aerosols would decline much more rapidly than the positive forcing associated with GHGs due to the much shorter atmospheric lifetime of aerosols, and this could potentially lead to a rapid acceleration of global warming (see, e.g., Arneth et al., 2009). Understanding the many and diverse effects of aerosols is also important for helping policy makers evaluate proposals to artificially increase the amount of aerosols in the stratosphere in an attempt to offset global warming (see Chapter 15).

Changes in land cover and land use. Human modifications of the land surface can have a strong local or even regional effect on climate. One notable example is the "urban heat island" effect on temperatures, described below and in Chapter 12. Globally, land cover and land use changes are important sources of several GHGs, such as the release of CO_2 from deforestation or CH_4 from rice paddies. Land use and land cover change can also yield a global climate forcing by altering the reflectivity of the Earth's surface—for example, by replacing forests (which absorb most incident sunlight) with cropland (which is generally somewhat more reflective). Satellite measurements provide an excellent record of how changes in land cover have influenced surface reflectivity over the last few decades, although in some cases there is uncertainty as to whether observed changes are directly human-induced, part of a feedback process, or attributable to natural changes. To estimate global patterns of land use change for the last several hundred years, scientists use historical and paleoecological records combined with land use models that can simulate changes in vegetation over time in response to both climatic and nonclimatic effects.

Most recent published estimates of the global climate forcing associated with land use and land cover change are in the range of −0.1 to −0.3 W/m^2, although some estimates are as large as −0.5 W/m^2, while others indicate a small positive net forcing (Forster et al., 2007). As noted above, an additional land-surface effect is the deposition of black carbon aerosols (soot) on white snow and ice surfaces, which leads to melting and has been estimated to yield a positive forcing of up to 0.2 W/m^2, although more recent estimates have suggested a somewhat smaller warming effect (Hansen et al., 2005). Thus, the total climate forcing associated with modifications to the land surface due to human activities since 1750 could potentially be positive or negative, but the balance of evidence seems to suggest a slight cooling effect.

Changes in solar radiation. As discussed in the next section, even small variations in the amount or distribution of energy received from the sun can have a major influence on Earth's climate when they persist for many thousands of years. However, satellite measurements of solar output show no net increase in solar forcing over the last 30 years, only small periodic variations associated with the 11-year solar cycle (Figure 6.9). Changes in solar activity prior to the satellite era are estimated based on a variety of techniques including observations of sunspot numbers, which correspond roughly with solar output (Figure 6.10). The available evidence suggest that solar activity has been roughly constant (aside from the 11-year solar cycle) since the mid-20th century but that it increased slightly during the late 19th and early 20th centuries. The total solar forcing since 1750 is estimated to be less than 0.3 W/m^2 (Forster et al., 2007).

Cosmic rays. Finally, it has been proposed that cosmic rays might influence Earth's cli-