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A Primer on Global Climate-Change Science

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Climate change is occurring, is caused largely by human activities, and poses significant risks for—and in many cases is already affecting—a broad range of human and natural systems.

—National Academy of Sciences (2010, 3)

The earth's climate system includes a series of checks and balances that, in the past, have worked together to maintain a stable climate. However, mounting evidence suggests that this balancing act has been tested over the last century and a half. Multiple indicators—including increasing air and ocean temperatures, increasing sea level, and retreating glaciers and sea ice—all point to a warming planet.

In this chapter, we present a primer on climate science and climate change. Climate, by its place-based definition, is an intuitive concept—we know it's usually warmer in Honolulu, Hawaii, than in Fairbanks, Alaska. However, climate science is composed of an intricate system that involves the interaction of air, water, ice, plants and animals, soils, and the solid earth. The complex nature of the earth's climate system presents a difficult scientific challenge, as it involves numerous interacting scientific disciplines. The interaction of multiple disciplines encourages scientific advances that speed up the evolution of climate science. This chapter summarizes several key elements of climate science to give readers a working background on the topic.

Climate and Weather

It is important to distinguish between weather and climate. Robert Heinlein (1978) provides us with a good starting point: "Climate is what you expect; weather is what you get." *Weather* refers to meteorological conditions at a particular time and place. The commonly used conversation starter: "How's the weather?" can be answered through a description of current outside conditions, including the temperature and the presence or absence of rainfall, cloud cover, humidity, and wind.

Weather forecasts are frequently used in a decision-making context and have been shown to be economically beneficial (Lazo et al. 2009). Weather forecasts are used to guide everything from the rather trivial issue of deciding whether to carry an umbrella or pack a coat to nontrivial issues associated with preventing or lessening weather-related damages or disasters. Weather predictions involve gathering observations and using mathematical models based on the principles of physics to describe probable atmospheric conditions for the next few days. The accuracy of weather forecasts has improved over the past couple of decades due to advances in observational techniques and modeling, and are extensively used to help us make informed decisions that save money and lives.

Forecast skill drops off after about ten days, chiefly because minute inaccuracies in observations incorporated into forecast models increase over time. This is *chaos theory*, often referred to as the "butterfly effect," after the idea that a butterfly flapping its wings in Brazil could create a localized swirl in atmospheric flow that could cascade and impact weather conditions at larger scales (such as creating a tornado in Texas). Of course, we are unable to monitor the movement of each of the world's butterflies, and thus forecast models tend to develop errors at longer timescales.

Climate refers to both the average and range of weather conditions that occur over an extended period of time (months, years, or centuries). The saying "climate is what we expect" therefore includes both a single average value and a range of outcomes taken from historic conditions. In this way, climate is composed of numerous samples of weather. Metaphorically, weather is one's mood whereas climate is one's personality, and weather is what you had for breakfast whereas climate is what is in your pantry. While climate is considered to summarize weather across a historic time period, it is important to note that changes in climate are noted when weather conditions exceed previously established ranges of variability. Although *weather* and *climate* are distinctly separate terms, just as there are daily fluctuations in atmospheric conditions (weather), there are also long-term fluctuations in climate. Deviations from established climate records can occur on a monthly or seasonal basis; for example, a wet winter in California is made up of a greater frequency or intensity of wet weather. They can also occur across longer timescales; for example, warming observed during spring across western North America over the last half-century is made of up warmer daytime high and low temperatures.

While we may not experience climate on a daily basis, as we do weather, it plays a strong role in defining human and environmental geography. Climate enables humans to settle in a specific area by defining natural resources such as water and agricultural potential within a local area. Climate influences human culture, from the articles of clothing we wear and the spices we use to the recreational activities we enjoy. While climate may be what we expect and depend upon, variations in climate disrupt the processes, such as food production, water availability, and energy demands, that societies are built upon. Variability in climate has acted, and continues to act, as a stressor on society, and economic losses from climate impacts persist despite modern advances and attempts to "climate-proof" resources and infrastructure. As we have become more aware of hazards associated with climatic variability, a greater emphasis has been placed on integrating seasonal climate forecasts into decision making, similar to our use of weather forecasts.

Earth's Climate System

The earth's climate system can be thought of as an elaborate balancing act of energy, water, and chemistry through the atmosphere, oceans, ice masses, biosphere, and land surface. These internal components of the climate system influence the fate of energy emitted by the sun and received by the earth. Solar energy, or solar *radiation*, serves as the impetus of energy in the earth's climate system. Roughly 30 percent of the solar radiation directed toward the earth is reflected back to space by bright, reflective surfaces, including snow cover, sand, and clouds. This is the same phenomenon that keeps a white car much cooler than a black car on a hot day.

Just as the sun emits energy, so does each object whose temperature is above absolute zero, including the Earth's surface. Absolute zero is the temperature at which, in theory, particles have no energy (Merall 2013). Emitted energy, or *radiation*, from both the sun and the earth travels in the form of waves that are similar to the waves moving across the surface of a pond.

However, the energy emitted by the sun and earth is quite different. Each emits radiation at distinctly different *wavelengths* (the distance between adjacent crests in the wave) and temperatures. While the hot sun emits energy at short wavelengths (referred to as *shortwave radiation,* including *visible light*), the much cooler earth emits radiation at longer wavelengths (referred to as *longwave,* or *thermal, radiation*).

For the earth to maintain a stable temperature, there must be a balance between the amount of radiation absorbed by the earth and the amount of energy emitted from the earth back to space. According to simple energy-balance calculations, the average temperature of the earth's surface in the absence of an atmosphere should be –18°C (0°F). Fortunately, the earth has an atmosphere that traps much of the thermal radiation emitted by the earth's surface, but allows most of the solar radiation to pass through. This acts somewhat like a one-way mirror seen in interrogation rooms on crime dramas. Certain trace gases in the earth's atmosphere, called *greenhouse gases,* selectively absorb longer wavelengths of energy emitted by the earth, heating the surrounding atmosphere. This energy is ultimately reflected back to the earth's surface. As a result, the earth's surface has a more difficult time cooling off, and the earth's surface and its lower atmosphere warm significantly.

Greenhouse gases are a natural component of the earth's atmosphere, with water vapor accounting for much of the greenhouse effect. The warming effect of water vapor can be observed during winter nights when the earth's surface has an extended period of time to cool off. A cloudy winter night is typically warmer than a clear winter night. Clouds and water vapor trap the heat radiating from the surface and keep surface temperatures from dropping as much as they would on a clear night. Overall, the natural greenhouse effect allows the average

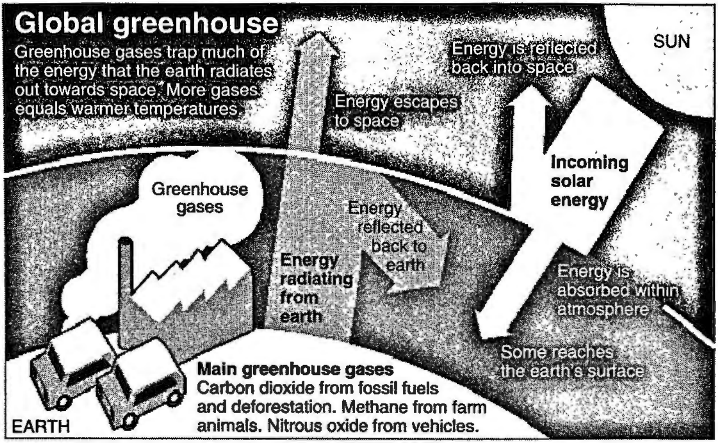

Figure 2.1
Fundamental dynamics of the greenhouse effect.

surface temperature of the earth to warm from a frigid –18°C (0°F) to a more comfortable 15°C (59°F). Thus, the chemical makeup of the atmosphere is crucial in establishing a climate that is hospitable to life (figure 2.1).

Our description of energy balance thus far applies to the earth as a whole. At local scales, the energy balance equation changes. To understand this, consider that solar radiation is much more intense near the equator than near the poles as a result of the curvature of the earth's surface and tilt of the earth's axis. The amount of solar radiation received in the tropics is much larger than that received at the poles. However, the rate at which earth emits energy (radiation) to space does not differ as dramatically from the equator to the poles. As a result, there is a net loss of energy near the poles and a net gain of energy in the tropics. Therefore, the ocean and atmosphere transport excess heat from the tropics to the heat-deficient polar regions via winds and ocean currents. If this transfer did not occur, there would be a rapid cooling of the poles and a dramatic warming of the tropics. Because our atmosphere and oceans redistribute this energy imbalance, much of our earth is livable.

The atmosphere responds to unequal heating of the earth's surface by generating atmospheric motion. *Atmospheric circulation* redistributes heat around the globe in an attempt to create energy balance. Atmospheric circulation responds relatively quickly to radiation. A familiar example of such a response is the sea breeze. During a typical summer day, the land surface heats up much faster than the nearby ocean surface. The warmer air over land becomes less dense and begins to rise. As this air mass rises, the cooler, denser air over the ocean flows inland to replace the rising warm air. As a result, the sea breeze cools inland locations and offsets temperature differences. A similar, more involved process serves to counter global-scale imbalances in heating: intense surface heating of the tropics creates warm buoyant air that rises to the upper troposphere and moves poleward while cold dense air near the poles sinks to the surface and moves toward the equator. This circulation, known as the *Hadley circulation*, redistributes energy around the globe and increases the area of our planet with temperatures hospitable to life.

Oceans are a key component of the climate system. Among the unique properties of water is its ability to store and transport vast quantities of heat. As surface water in the tropics is heated, large-scale ocean currents, driven by atmospheric circulation patterns, transport heat poleward. This process parallels the atmosphere's redistribution of energy across the globe, but it operates on much longer timescales. Consider, for example, the circulation of the North Atlantic basin. The northward-flowing Gulf Stream transports warm water from the Gulf of

Mexico toward northern Europe. It is believed that the Gulf Stream helps to stabilize the mild climates of northwestern Europe (Seager 2006). The ocean also plays a role in determining the chemical composition of the atmosphere due to its ability to take up and release gases important in establishing the earth's climate, such as carbon dioxide, or CO_2.

The *cryosphere* comprises that portion of the planet's water that is locked away as ice, including the Greenland and Antarctic ice sheets, sea ice in the Arctic and Southern Oceans, and all other snow- and ice-covered surfaces. An important property of the cryosphere is its ability to reflect solar radiation. Large ice sheets reflect between 70 and 90 percent of solar radiation, allowing very little radiant energy to warm the surface. If the ice sheet were to grow in extent in response to cooling, a greater amount of solar radiation would be reflected back to space, thereby further cooling the planet. This is an example of a *climate feedback,* where an initial change in one aspect of the dynamic climate system (e.g., slight cooling) interacts with other components of the system and can then alter the magnitude of the original change. The growth of the ice sheet during a glacial period acts as a positive feedback on the climate system. A *positive feedback* involves a coupled system that amplifies the initial change. Conversely, as the ice sheet recedes during warming, more solar radiation reaches the earth's surface, accelerating the warming of the planet and the melting of the ice sheet.

The land surface and the biosphere both affect and are affected by atmospheric temperature and humidity, and can alter the amount of solar radiation reflected back to space. Vegetation also plays a key role in the *carbon cycle,* which is the exchange of carbon among atmosphere, ocean, and land (biosphere included). Plants are active participants in the carbon cycle as they absorb CO_2 through photosynthesis and expel CO_2 through respiration. It is currently thought that plants take up more carbon from the atmosphere than they emit, and are therefore net *sinks* of atmospheric carbon (Le Quere et al. 2009). By contrast, changes in land use—such as deforestation and subsequent burning of forest material—release stored carbon into the atmosphere and are net *sources* of carbon to the atmosphere. In particularly productive ecosystems such as tropical rainforests, deforestation not only provides a source of atmospheric carbon, but also removes a net sink that would otherwise take up atmospheric carbon to build woody biomass through photosynthesis.

The Importance of Greenhouse Gases to Climate

In 1824, the French scientist Joseph Fourier hypothesized that the average temperature of the planet is warmer because of the existence of the earth's atmosphere. He claimed that the warming effect of the atmosphere on the earth's surface was similar to the way a plant warms when it is encased in a house of glass. Fourier called this phenomenon the *greenhouse effect,* and the name stuck.

The composition of the earth's atmosphere governs the climate of the planet and establishes conditions vital for life. The ability of greenhouse gases to warm the surface of the planet depends on four main factors: their efficiency in absorbing heat energy, their concentration and distribution in the atmosphere, and how long they remain in the atmosphere.

Although the atmosphere is primarily composed of nitrogen and oxygen, these gases do not interact with the thermal radiation emitted by the earth. However, greenhouse gases—including carbon dioxide (CO_2), methane (CH_4), nitrous oxide

Box 2.1
Definition of Climate

> The word *climate* is derived from the Greek word *klima*, a term that refers to the angle of the sun's rays as they strike the earth's surface. The Greek geographer Ptolemy proposed that changes in tilt according to latitude affected the length of the day and the brightness of the sun—ultimately altering the nature of climate and the viability of life on earth. In addition, geographic differences in the amount of solar radiation over the seasons, along with the position of the continents and mountains, result in regional variations in temperature, wind, and precipitation patterns. The regional climates that are commonly accepted today come from Wildimir Koppen's subdivision of the earth based on temperature, precipitation, and distribution of natural vegetation. Climate ultimately represents the complex web of factors that define the atmospheric conditions in a determined geographical area for a prolonged period of time (years, decades, centuries, and geological eras).

(N_2O), halocarbons, ozone (O_3), and water vapor (H_2O)—are very effective at absorbing thermal radiation. The absorption of energy by air molecules heats the atmosphere, which then reradiates energy back to the surface of the earth. This process prevents the earth from cooling. Another important property of greenhouses gases is that while they are effective at absorbing thermal radiation, they are essentially transparent to solar radiation. Hence, the overall influence of greenhouse gases is to warm the planet to approximately 33°C (59°F), which is remarkable given their seemingly small concentrations in the makeup of the atmosphere.

Two planets closest to the earth offer good examples of how changes in atmospheric composition can lead to changes in surface temperatures. Although Venus is closer to the sun than the earth and thus receives a greater amount of incoming solar radiation, clouds engulf the planet, reflecting nearly 75 percent of the solar radiation. As a result, the solar radiation absorbed by Venus is actually less than that absorbed by earth. However, the thick, carbon dioxide–rich (97 percent CO_2) Venusian atmosphere is highly effective at keeping thermal radiation from escaping to space, resulting in an average surface temperature of 470°C (878°F). In contrast, Mars has a very thin atmosphere with a minimal greenhouse effect. As a result, most of the heat radiated from the surface of Mars escapes to space, and the average surface temperature on Mars is about –60°C (–76°F).

Efficiency of Greenhouse Gases in Absorbing Heat

Scientists estimate the heat-trapping efficiency of different greenhouse gases using an index called *global warming potential* (GWP). This represents the ratio of energy trapped by the earth-atmosphere system for a given mass of a particular gas in comparison with the ability of the same mass of CO_2 to trap energy over a specified period of time. The GWP of CO_2 is defined as 1. By comparison, methane has a GWP of 21, meaning that a given mass of methane can heat the planet twenty-one times as much as the same mass of CO_2. Other greenhouse gases have even larger GWPs. Nitrous oxide and halocarbons have GWPs of 300 and over 5,000, respectively. So although carbon dioxide is notorious for its role in global warming, other, less well-known greenhouse gases also play potent roles in the global warming process.

Quantities of Greenhouse Gases

Scientists can quantify the composition of the atmosphere prior to the historical record by examining other physical records that provide a stand-in for direct measurements. Bubbles of air embedded within ice cores extracted from the Greenland and Antarctic ice sheets reveal a substantial amount of information on past changes in climate. The cores tell us that from about 800,000 years ago until the beginning of the Industrial Revolution in the late 1700s, CO_2 varied from about 180 parts per million (ppm) during glacial periods to about 280 ppm during interglacial periods (Lüthi et al. 2008). During interglacial periods, such as the one we are in today, levels of atmospheric CO_2 have previously been relatively constant, maintained through a balance of carbon exchanges between the atmosphere, biosphere, and oceans. *Anthropogenic*, or human-made, carbon emissions have resulted in an imbalance in the carbon cycle and an accumulation of carbon in the atmosphere. Atmospheric CO_2 levels at Mauna Loa, Hawaii, reached as high as 400 ppm in May 2013 (Mohan 2013). The rate of increase of atmospheric CO_2 since 2000 has a higher average than the rate of increase for each decade going back to the 1960s (Tans and Keeling 2013). The question is: how will these high levels of CO_2 affect our climate?

US emissions of carbon dioxide from fossil fuel combustion in 2011 were about 11 percent above 1990 levels, accounting for about 78 percent of US greenhouse gas emissions weighted by GWP from 1990 to 2011 (EPA 2013a). Likewise, methane and nitrous oxide are naturally occurring gases that have seen their atmospheric concentrations increase due to industrial and agricultural activities and biomass burning. Figure 2.2 shows US greenhouse gas emissions for 2011 by gas. Throughout this book the term *forcing*, or *climate forcing*, refers to a mechanism that alters the amount of energy contained within the climate system. Figure 2.3 shows global radiative forcing by gas for 2011.

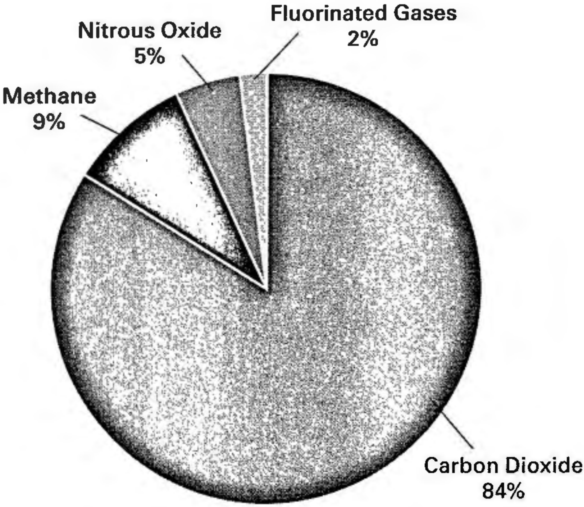

Figure 2.2
United States emissions of greenhouse gases by type in 2011.
Source: US Environmental Protection Agency (2013a). Inventory of US Greenhouse Gas Emissions and Sinks 1990–2011.

Halocarbons do not exist in nature, but are manufactured for use in refrigeration units and foaming agents. The most notorious halocarbons are chlorofluorocarbons (CFCs), which are potent greenhouse gases that also destroy the ozone layer. Alternative halocarbon compounds, such as hydrofluorocarbons and perfluorocarbons, were introduced as substitutes for chlorofluorocarbons. The ozone layer protects life from the dangerous ultraviolet rays that have detrimental effects on terrestrial and marine life (World Meteorological Organization 2002). Because of the strong scientific evidence linking emissions of CFCs to the depletion of the ozone layer and a global policy to curtail the usage of CFCs, the chlorine levels in earth's ozone layer have declined. This success story provides hope for science-based policy action for other environmental problems the earth faces. However, as a European climate authority notes, "The timing of the ozone layer recovery and in particular the closure of the ozone hole is particularly difficult to forecast since the variability and future evolution of the ozone layer is affected by a number of processes, among them climate change which exerts an influence on atmospheric dynamics and—via temperature changes—on ozone chemistry" (European Space Agency Ozone Climate Change Initiative 2013, 2–3).

Lifetimes of Greenhouse Gases

The atmospheric lifetime of a gas refers to the average amount of time a gas molecule remains in the atmosphere before being

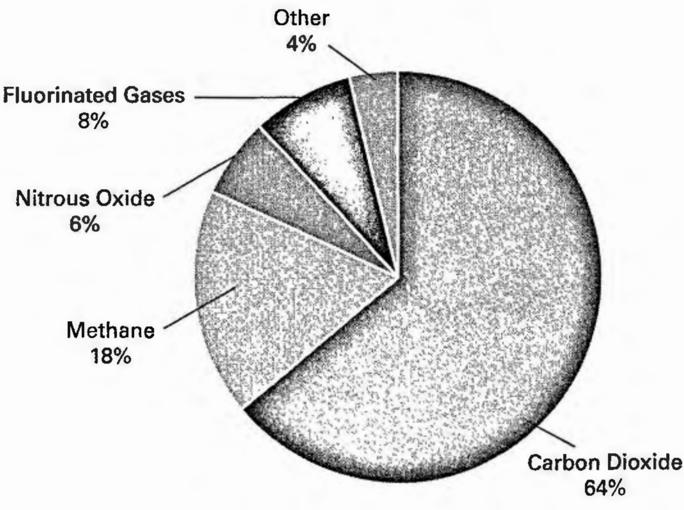

Figure 2.3
Global radiative forcing of all long-lived greenhouse gases in 2011. *Source:* US National Oceanic and Atmospheric Administration (2012).

washed out. Water in the atmosphere has a short lifetime of about 10 days. Consequently, it is not well mixed in the atmosphere (as we can observe in the passage of clouds in the sky) and is widely variable across the globe. Other greenhouse gases have long lifetimes of decades to centuries. These gases are well mixed in the atmosphere, because they are transported across the globe by atmospheric circulation. The long lifetimes of greenhouse gases mean they have a cumulative effect on global climate changes. For example, today's emissions of carbon dioxide are likely to remain in the atmosphere for twenty to one hundred years or more.

Industry and Greenhouse Gases

Atmospheric concentrations of greenhouse gases have largely been balanced by the carbon cycle over the life history of the planet. Carbon cycles through the atmosphere via photosynthesis and respiration by land and sea flora, via air-sea exchanges (*fluxes*), and via "slow-turnover" geologic processes. While important for the evolution of the atmosphere, the relatively slow pace of the geologic carbon cycle (millions of years) is important only in controlling long-term variations in levels of atmospheric carbon dioxide.

The Industrial Revolution marked a turning point in the balance of energy in the earth's climate system. The rise of industry and technology resulted in an increase in the burning of wood and coal that serve as *sources* of carbon into the atmosphere. At the same time, changes in land use, including deforestation, worsened this imbalance by removing a potential sink for carbon. Carbon sources and sinks refer to parts of the carbon cycle that transfer carbon into and out of the atmosphere, respectively. Today, human activity is responsible for releasing approximately 9 billion metric tons of carbon per year into the atmosphere, with the ocean and land absorbing approximately half of that carbon (Le Quere et al. 2009). The accumulation of atmospheric carbon is analogous to a rising pool of water in a bathtub with a drain that is partially closed. The drain represents the sinks for atmospheric carbon in the oceans and the land, whereas the output of the faucet represents carbon in the atmosphere from sources such as fossil fuel burning and land-use change. If water comes out of the faucet faster than the drain can remove it, the water level in the bathtub will rise. Similarly, if sources of carbon outweigh the sinks, the amount of carbon in the atmosphere will continue to rise.

Electricity generated by the burning of fossil fuels accounted for more than a third of manmade carbon dioxide released in 2011 in the United States (EPA 2013b). In contrast, other energy sources—including nuclear, solar, wind, hydroelectric, and geothermal energy sources—emit minimal, if any, greenhouse gases. Using biomass to generate electricity can also reduce net

Box 2.2
Charles David Keeling, 1928–2005

In 1958, Charles David Keeling, a professor at the Scripps Institution of Oceanography at the University of California at San Diego, began to collect a continuous record of atmospheric carbon dioxide concentrations from towers on the Mauna Loa Observatory in Hawaii. Prior to his observations, it was unclear whether anthropogenic CO_2 emissions accumulate in the atmosphere or are absorbed by vegetation and the oceans. Keeling's measurements have confirmed increased CO_2 levels and are a leading piece of evidence of anthropogenic effects on atmospheric chemistry. Many consider his work to be the single most important environmental dataset of the twentieth century.

Box 2.3
The Colonials

> Colonial Americans were sensitive to British criticism of the cold American climate and, according to science historian James Fleming (1998), argued that their climate was improving as the forests were cleared. In 1721, Cotton Mather believed that the North American region was getting warmer: "Our cold is much moderated since the opening and clearing of our woods, and the winds do not blow roughly as in the days of our fathers, when water, cast up into the air, would commonly be turned into ice before it came to the ground." Benjamin Franklin agreed: "cleared land absorbs more heat and melts snow quicker," but concluded that many years of observations would be necessary to settle the issue of climatic change (Fleming 1998, 24).

greenhouse gas emissions. Forest trimmings, orchard prunings, livestock manure, cheese-processing waste, restaurant waste, gases from wastewater treatment plants, and gas from landfills are all forms of biomass. Biomass generally removes carbon dioxide from the air when growing and emits methane, which is a more potent greenhouse gas than carbon dioxide, when it decays. When managed sustainably, displacing the use of fossil fuels with full combusted or anaerobically digested biomass to generate electricity can reduce net greenhouse gas emissions.

The transportation sector is the second biggest source of carbon dioxide emissions in the United States. Every gallon of gasoline consumed releases about 2.5 kilograms (5.5 pounds) of carbon into the atmosphere. Fuel economies of many automobiles have improved dramatically over the past few decades because of technological improvements, but the carbon dioxide emitted from vehicles in the United States is still approximately

Box 2.4
Guy Stewart Callendar, 1898–1964

Beginning in 1938, the British engineer and scientist Guy Stewart Callendar identified important links between the burning of fossil fuels and global warming (Fleming 2007). He compiled weather data from stations around the world that showed a warming trend of 0.5°C (0.9°F) in the early decades of the twentieth century. He estimated a 10 percent increase in atmospheric CO_2 levels based closely on the amount of fuel burned between 1900 and 1935, and hypothesized the warming was due to the increase in atmospheric CO_2 concentrations. Today, the theory is called the *Callendar effect*.

equal to that emitted from all sources in India (even though the population of India is nearly four times that of the United States).

In addition to CO_2 emissions, more than half of today's methane emissions are attributable to human activities, such as burning biomass, cultivating rice, creating landfills, and managing livestock (Solomon et al. 2007, chapter 7.4.1). Although much lower in atmospheric concentrations compared to CO_2, methane is the second most important greenhouse gas due to its strong GWP. Atmospheric concentrations of methane have increased by more than 150 percent since the beginning of the Industrial Revolution as a direct result of human activities (EPA 2013a, Introduction, 5). Methane releases from agricultural and natural sources are expected to increase in a warming planet, regardless of human activity. Studies argue that warming may melt huge expanses of high-latitude permafrost and release large reserves of methane that have been locked away in deep soils (Zimov, Schuur, and Chapin 2006) and beneath the oceans (Pearce 2007).

Aerosols

In addition to gases, the atmosphere contains suspended solid and liquid particles called *aerosols*. Aerosols can range in size from tiny molecular clusters to particles visible to the human eye. The principal sources of aerosols include both natural sources, such as dust, vegetation, sea spray, and volcanoes, as well as anthropogenic sources from fossil-fuel combustion and biomass burning. Like greenhouse gases, aerosols play a role in the earth's climate and have increased in the atmosphere since the Industrial Revolution. However, unlike greenhouse gases that act primarily on *longwave* radiation and have long atmospheric lifetimes, aerosols primarily interact with *shortwave* radiation and have short lifetimes.

Unlike greenhouse gases that are not visible to the human eye, aerosols can be seen in sunlight and often play a role in brilliant autumn-hued sunsets. Aerosols come in different colors and differ in their ability to reflect and absorb sunlight. Light-colored aerosols reflect incoming solar radiation, thereby decreasing the amount of energy that reaches the earth's surface. Much as wearing light-colored clothing keeps you cooler when you're in the sun, these aerosols tend to cool the planet. In contrast, dark aerosols that are a byproduct of incomplete fossil fuel and biomass combustion—such as black carbon—absorb solar radiation and heat the atmosphere. Additionally, when black carbon from the atmosphere is deposited on mountain snowpack and glaciers, it increases the amount of solar radiation absorbed and contributes to additional warming. Recent studies show that the additional energy absorbed by black carbon is nearly half the total warming influence of anthropogenic greenhouse gases, second only to carbon dioxide in terms of its contribution to global warming (Ramanathan and Carmichael 2008; Bond et al. 2013).

Over the last two hundred years sulfate aerosols, a byproduct of emissions from fossil-fuel combustion, have increased enormously. In parts of the world that consume large amounts of sulfur-rich coal, such as China and central Europe, sulfate emissions partially offset the warming effects of high levels of greenhouse gases in the short term. But emitting these aerosols to lessen the enhanced greenhouse effect, as some geoengineers and others suggest, is problematic for several reasons. First, sulfates combine with water vapor to form sulfuric acid, the principle component in acid rain. Second, the short lifetimes of aerosols (days to weeks) result in regional impacts, while long-lived greenhouse gases are diffused across the globe. Third, efforts to counter greenhouse gas–fueled warming with aerosols would require massive, continual, and widespread emissions. Finally, loading our atmosphere with aerosols may result in undesirable and unforeseen consequences on a host of processes crucial to life on our planet. The concept of adding aerosols to the atmosphere to lessen the warming of the planet is further discussed in the section on geoengineering in chapter 5 of this book.

In contrast, due to the strong warming influence of black carbon and the fact that aerosol lifetimes are very short, some have suggested that efforts to curb black carbon emissions are a cost-effective route to temper warming trends. Emissions of black carbon are particularly high in southern Asia, where 40 percent of black carbon emissions come from solid biomass used for residential cooking (EPA 2012). Efforts to provide alternatives to such fuels in parts of the developing world may not only have immediate benefits to climate, but also may reduce the health impacts associated with poor air quality in such regions. In comparison to the worldwide effort to reduce carbon emissions, many believe that reduction of black carbon emissions is a more acceptable and readily available option for mitigating climate change.

Climate Change as an Environmental Problem

Climate change was recognized as a global environmental problem for the first time in the late 1970s. James Hansen, an American climatologist, advanced the Callendar hypothesis that fossil fuel burning was heating the planet. At the first World Conference on Climate, held in Geneva in 1979, many scientists warned that climate changes driven by human activity would detrimentally affect humankind and the environment. The conference attendees invited all heads of state to heed their warnings about climate change and enact "necessary policies for the well-being of humanity." The worldwide response to this invitation and later warnings are discussed in chapter 5.

The Climate Puzzle

Numerous natural and anthropogenic factors have produced today's climate. The studies of past climates (in a field called *paleoclimatology*) and modern climate (called *climatology*) describe the processes and patterns of the earth's climate system and the forces that drive climate variability and change. If we can thoroughly understand past variations, we are more apt to understand recently observed and projected changes in climate. Natural variations in climate—including oscillations in large-scale wind patterns, changes in oceanic circulation, solar variability, and variations in the earth's orbit—occur on timescales ranging from years to decades to tens of thousands of years.

Box 2.5
James E. Hansen

Although James Hansen's early research focused on the atmosphere of Venus, he soon was drawn to the exciting and innovative research being done regarding earth's climate. He has since added greatly to our body of knowledge on climate change through the development of climate models that numerically simulate global climate and that help us understand the complexities of the climate system and test hypotheses of climate change. Some of Hansen's initial projections of global warming trends made in the early 1980s have been fairly accurate and have been validated by the continued warming of the planet. Based on his research, Hansen concludes:

> Climate system inertia means that it will take several centuries for the eventual extreme global warming mentioned above to occur, if we are so foolish as to burn all of the fossil fuel resources. Unfortunately, despite the ocean's thermal inertia, the transient climate phase this century, if we continue business-as-usual fossil fuel burning, is likely to cause an extended phase of extreme climate chaos. As ice sheets begin to shed ice more and more rapidly, our climate simulations indicate that a point will be reached when the high-latitude ocean surface cools while low-latitudes surfaces are warming. An increased temperature gradient, i.e., larger temperature contrast between low and high latitudes, will drive more powerful storms. ... The science of climate change, especially because of the unprecedented human-made climate forcing, includes many complex aspects. This complexity conspires with the nature of reporting and the scientific method itself, with its inherent emphasis of caveats and continual reassessment of conclusions, to make communications with the public difficult, even when the overall picture is reasonably clear. (2013)

Hansen for many years was the director of the NASA Goddard Institute for Space Studies in New York. In 2013 he announced that he was retiring from NASA to devote himself to becoming an activist for climate change.

Natural Climate Variability

Observations suggest that global climate change is currently underway. Paleoclimatic data reveal that change has occurred in the global climate throughout the earth's history. Modern climate observations represent a mere fraction of climate history. How can we know whether the current changes are part of the natural ebb and flow of global climatic changes, or if they are extremely unusual against the backdrop of the earth's history, and thus point to human-caused factors? Like a detective trying to solve a case, paleoclimatologists search for pieces of evidence to solve the climate puzzle. Although the thermometer wasn't invented until the seventeenth century, scientists are able to reconstruct climate before the era of modern instruments through *proxy data*. Proxy data are essentially "natural" historical recording systems of climatic conditions and the chemical makeup of the atmosphere.

Proxy data are found in objects familiar to most of us, such as trees and fossil records, and objects not as familiar to us, such as lake and ocean sediments. The most widely recognizable source of proxy data is tree rings, which record year-to-year variations in tree growth. Some trees are sensitive to energy requirements (temperature), while others might be sensitive to moisture requirements (precipitation). For example, trees in a semi-arid climate might be able to grow at a faster rate during unusually wet years, whereas those near the upper tree line, where moisture is usually not a limiting factor, might grow at a faster rate during warmer periods. Trees can provide a trace of climate over their lifespan of some hundreds to even thousands of years in some cases. Other sources of proxy data include sediments, ice cores, corals, and the geologic record. As mentioned previously, cores extracted from glaciers

Box 2.6
Svante Arrhenius, 1859–1927

"Is the mean temperature of the ground in any way influenced by the presence of the heat-absorbing gases in the atmosphere?" (Arrhenius 1896, 237). In 1895, the Swedish chemist Svante Arrhenius presented an answer to this question to the Stockholm Physical Society (Fleming 1998). Arrhenius did not pursue an answer out of any great concern for increasing levels of CO_2; rather, he was attempting to explain temperature changes between glacial and interglacial periods.

> Arrhenius formulated a heat budget for the planet in which changes in the atmospheric levels of carbon dioxide are matched by changes in surface temperature. With this model, he concluded that the temperature of the Arctic region would increase by 8–9°C (14°–16°F) if atmospheric CO_2 concentrations tripled from preindustrial levels. Arrhenius (1908, 51) went on to describe the "hot-house theory" (greenhouse effect), calling on earlier studies suggesting that the earth's surface temperature would be about 33°C (59°F) cooler in the absence of atmospheric gases. In his work he also noted that the increased production of CO_2 "by the advances of industry" could alter climate "to a noticeable degree in the course of a few centuries" (1908, 54). However, he maintained that this increased use of fossil fuels could be advantageous for the climate, resulting in "ages with equable and better climates, especially as regards the colder regions of the Earth" (1908, 63).

In 1899, Nils Ekholm, an associate of Arrhenius, suggested that rates of coal burning could double the concentration of atmospheric CO_2 and "undoubtedly cause a very obvious rise of the mean temperature of the Earth." In Arrhenius's 1908 book, *Worlds in the Making*, he popularized this hypothesis. Arrhenius considered that such emissions would be fortuitous given that "a new ice period ... will drive us from our temperate countries into the hotter climates of Africa." Arrhenius speculated on a "virtuous circle" in which fossil fuel burning could delay a rapid return to the ice ages. Arrhenius's CO_2 theory of climate change fell out of scientific favor and was not revived in its modern form until the mid-1950s (Fleming 1998).

can extend hundreds of meters below ground and reveal the chemical composition of the air bubbles imprisoned in glacial ice. Scientists can use pollen samples from lakebeds to identify vegetation that flourished nearby millions of years ago, and use this to infer climatic conditions suited to such vegetation.

Climate reconstructions have greatly advanced our understanding of the climate system and natural climate cycles. Slow changes in earth's orbit are the leading initiator of the glacial-interglacial cycles that have been the pacemaker of global climate over the past two million years; each cycle requires approximately 100,000 years. The glaciers covering North America and Europe during the last glacial period began receding 18,000 years ago.

The transition between glacial conditions and the interglacial conditions that we are experiencing today was not a smooth one; it was marked instead by a number of abrupt changes that occurred over decades (Severinghaus et al. 1998), though not as quickly as those depicted in the 2004 movie *The Day after Tomorrow*.

Some models have suggested that an abrupt change in climate could slow down deep-ocean circulation (called *thermohaline circulation*). This circulation is driven by slight differences in *water density* that arise in response to variations in water temperature and *salinity*, or salt content. At the surface of the ocean, winds guide oceanic currents that work with the atmosphere to redistribute heat across the globe. For example, the Gulf Stream pulls warm salty water away from low latitudes and toward the high latitudes, releasing heat into the North Atlantic and moderating climate across northwestern Europe. As this salty water moves into higher latitudes, it cools and increases in density and ultimately sinks to the bottom of the ocean, thereby churning the thermohaline circulation.

Oceanic circulation is more apt to be maintained if changes are of a gradual nature. By contrast, discharge of freshwater into the North Atlantic that could result from rapid melting of freshwater glacial ice may shut down circulation by decreasing the density of surface water (McCarthy et al. 2001, 17).

Thirteen thousand years ago, global temperatures were rebounding after the previous glacial period. Suddenly, however, within a decade, glacial conditions rapidly returned to the high latitudes of North America and Europe as high northern latitudes cooled nearly 6°C (11°F). This return to glacial conditions is known as the Younger Dryas, named for a flower tolerant of cold conditions found in the pollen record across much of Europe during the period. Scientists hypothesize that this abrupt cooling resulted from an influx of fresh water into the salty waters of the North Atlantic released after the melting of the Laurentide ice sheets over eastern Canada. This freshening of the North Atlantic slowed down thermohaline circulation and the Gulf Stream that delivers warm water from the balmy subtropics to northwestern Europe. Archaeologists note that the onset of this cooler and drier period coincided with the beginning of agriculture in northern Mesopotamia (Calvin 2002). Fluctuations in the climate likely had an adverse impact on the food supply of hunter-gatherers, creating an incentive for developing agriculture as a more stable and reliable food source.

The Medieval Warm Period and the Little Ice Age are the two most noted "natural" climate cycles of the last millennia. These variations in climate were modest, compared to the Younger Dryas, yet had impacts on growing population centers in Europe. During the Medieval Warm Period (in the tenth to fourteenth centuries), warmer Northern Hemisphere temperature (similar to temperatures during the twentieth century, but cooler than present) allowed for the Viking colonization of Greenland. However, the onset of the Little Ice Age (in the fifteenth to nineteenth centuries) ushered in cooler temperatures, which resulted in the collapse of these colonies. Northern Hemisphere temperatures were about 1°C (1.8°F) cooler than twentieth-century conditions, and were most notable across parts of Europe. These seemingly benign changes in global climate posed an additional stressor to society, impacting agricultural productivity and leading to starvation and an overall deterioration in human health. The Medieval Warm Period and Little Ice Age are hypothesized to be a result of a combination of solar, volcanic, and oceanic variability.

On much shorter timescales, phenomena such as the El Niño Southern Oscillation and volcanic eruptions have important but short-lived impacts on global climate. El Niño's Southern Oscillation is a coupled atmosphere-ocean phenomenon that channels interannual (year-to-year) fluctuations in ocean temperatures over the tropical East Pacific into global fluctuations in climate. For example, under El Niño conditions, when ocean surface temperatures off the coast of Peru are unusually warm during winter, the southern half of the United States experiences cooler and wetter winters than normal, while the northern half of the country from the Great Lakes westward to the Pacific Northwest experiences warmer than normal winters due to a change in the location of the storm track. Typically, El Niño conditions result in a spike in mean annual global temperatures by a few tenths of a degree, while La Niña conditions (the reverse of El Niño conditions) result in a short-lived cooling of global temperatures. Year-to-year variations in the natural climate system are one reason why increased greenhouse gas concentrations do not result in yearly increases, though long-term warming trends are clear.

Volcanic eruptions have long been implicated in climate variations. Volcanic eruptions release huge quantities of ash, aerosol droplets, and volcanic gas, including sulfur dioxide and carbon dioxide, into the atmosphere. The sulfur dioxide gas masses can be injected high into the atmosphere, where they form bright reflective aerosols that shield the earth from the sun's rays and lead to a short-lived (up to a few years) global cooling (USGS 2012). This effect was noted in the last few decades following the eruption of El Chichon in Mexico in 1982 and Mount Pinatubo in the Philippines in 1991. These recent volcanic eruptions pale in comparison to the volcanic activity from Mount Tambora that preceded the so-called Year without a Summer in 1816. That summer was marked by unusually cool conditions across much of Europe and the eastern United States. Cold temperatures that year resulted in widespread crop failure across developing North American settlements and exacerbated food crises and epidemics across much of Europe; it has been labeled "the last great subsistence crisis in the Western world" (Post 1977, i).

Global Climate Models

Scientists who study changes in the earth's climate system cannot follow classical experimental methods that include a "control group" because we only have one earth. In the absence of a control group, scientists study dynamics of global climate change by constructing numerical computer models of the climate system. Vast improvements in our understanding of the climate system have been made over the last three decades through a combination of advancements in computation capabilities, high-quality observations, theory, and interdisciplinary science.

Global climate models, or GCMs, are physics-based numerical models that represent our best understanding of the processes and interactions of components of the earth's climate system. These models have been used to explain past changes in climate, and are used today in seasonal climate outlooks and long-term climate predictions. Several modeling groups across the world have developed GCMs. While this may appear to be a redundant exercise, these GCMs have varying levels of complexity and computation demand, and thus yield slightly different results when the same experiment is conducted. Using several models to conduct the same experiment is similar to how biologists use many lab rats in an experiment to examine how well a new serum works to cure an illness. This "probabilistic approach" is generally preferred over relying on the outcome of a single model. It not only tests the robustness of outcomes but also can better frame the odds of varying levels of change.

The fundamental issue in climate change is whether observed changes in climate have resulted from natural or human forcing, or from some combination of the two. Numerous studies have been conducted to determine the extent to which climate changes realized during the twentieth century are the result of natural variability (Karl and Trenberth 2003). Models that account solely for natural forcing, including volcanic eruptions and solar variability, are unable to replicate observed twentieth-century changes in temperature, ocean heat content, and global processes. Models are only able to replicate the observed changes in climate after including anthropogenic forcing, including the observed increases in greenhouse gases and aerosol concentrations—providing strong evidence that a majority of the warming observed during the twentieth century is attributable to increased levels of atmospheric greenhouse gases. This evidence was presented to the White

House in spring 2001 in a report that concluded, "Greenhouse gases are accumulating in earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. ... The changes observed over the last several decades are likely mostly due to human activities" (National Academy of Sciences Committee 2001, 1). In 2007, the Intergovernmental Panel on Climate Change (IPCC) stated, "Since the start of the industrial era (about 1750), the overall effect of human activities on climate has been a warming influence. The human impact on climate during this era greatly exceeds that due to known changes in natural processes, such as solar changes and volcanic eruptions" (Solomon et al. 2007, FAQ 2.1).

Scientists have used many sources of data to investigate the dynamics of the climate system in order to expand and improve the scientific observations that are the basis for GCM calculations. In the absence of a dynamic climate system, it would be quite easy to calculate the net change in global temperature (a 1°C warming) due to a doubling of CO_2. Unfortunately, the climate system is much more complex. A slight warming in surface temperature results in a cascade of processes known as *climate feedbacks* that interactively alter components of the system and can affect the original change. For example, in a warming planet, the increase in evaporation and the ability of a warmer atmosphere to hold more water vapor both strengthen the greenhouse effect, thereby amplifying warming. However, increased water vapor may also lead to increased cloud formation, reflecting solar radiation and moderating the warming. Scientists suggest that clouds are the largest wildcard in climate due to their ability to trap outgoing thermal radiation (and thus help to warm the planet) and reflect incoming solar radiation (thus helping to cool the planet; Emanuel 2012). Other uncertainties include the carbon cycle and biotic response to climate change.[1]

Existing models do not currently account for the release of large quantities of methane, a gas with high heat-trapping potential, from the immense tracts of permafrost now melting due to global warming (Zimov et al. 2006; Williamson, Saros, and Schindler 2009; Ruppel 2011). Additionally, a recent study reveals that large urban areas produce enough heat during winter months to influence the width of the jet stream and the nature of other climate processes (Scripps Institution of Oceanography 2013). Were all these elements taken into consideration in the development of climate change models, the projected heat increases and the potential consequences of global warming would be even worse than current models indicate.

Climate feedbacks play a critical role in future climate scenarios by indicating how sensitive climate is to changes in the amount of energy to the system. Our current best estimate of the earth's *climate sensitivity*, a measure of the change in global temperature in response to a doubling of atmospheric CO_2, is an increase in temperature between 2–4.5°C (3.6–8.1°F; Alley et al. 2007). This increase is substantially larger than the 1°C (1.8°F) warming in global mean temperature projected to occur due only to a doubling of CO_2.

Finally, future climate change depends on the trajectory of global demographics as well as energy sources, land use, and the effects of globalization. The IPCC's emission scenarios (IPCC 2000) were used to form a basis for projected changes in emissions of greenhouse gases and aerosols. Scenarios range from optimistic future conditions, where population levels stabilize and levels of greenhouse gas emissions are reduced, to pessimistic future conditions in which population and greenhouse gas emissions continue to grow. More recently, an equivalent set of trajectories called *representative concentration pathways* was devised to provide a more flexible set of scenarios. These representative concentration pathways focus on the amount of additional energy trapped by the earth-atmosphere system. These scenarios are run through a set of GCMs to provide scientists with a confidence range for projections of future climate change.

The IPCC produces reports, based on hundreds of scientific studies, that summarize the current understanding of observed climate change. The reports provide climate projections and describe climate impacts and adaptation and mitigation measures. The fourth assessment report, released in 2007, stated, "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (IPCC 2007a, 2).[2] According to the National Oceanic and Atmospheric Administration (2013), observations show that "the combined average temperature over global land and ocean surfaces for May 2013 tied with 1998 and 2005 as the third warmest on record, at 0.66°C (1.19°F) above the 20th century average of 14.8°C (58.6°F)." Furthermore, observed global temperature trajectories have been broadly consistent with the GCM-based projections established by James Hansen in the 1980s. Perhaps more alarming is the fact that the changes have occurred faster than predicted. For example, observed increases in sea ice retreat, snow cover loss, and mass loss of Greenland's ice sheet have exceeded climate projections to date (e.g., Stroeve et al. 2007, Pierce et al. 2008). Scientists have revised the IPCC's predictions for Arctic sea ice (IPCC 2007b, 659), and now predict the Arctic may be nearly ice-free in summer between 2030 and 2050, decades earlier than originally predicted (Wang and Overland 2009; IPCC 2013, 23).

Conclusion

We have reviewed the basics of climate science, emphasizing how the earth's climate system balances both energy and the atmospheric composition to sustain life on the planet. This balance is threatened by an abrupt rise in greenhouse gas concentrations since the Industrial Revolution. Ambient levels of carbon dioxide increased from about 280 ppm in the mid-1800s to approximately 400 ppm in 2013. Levels of atmospheric CO_2 are anticipated to reach between 600 and 1,000 ppm by the end of the twenty-first century.

The science of climate change can be thought of as a movie that has been made by hundreds of directors and that takes viewers from billions of years ago to the present. But it is a film with many blurry images and empty frames. The goal of research in climate science is to refine these images and fill in the missing frames to provide context to the plot. As the movie chronicles actions that have brought us to the current era of global climate change, the challenge is to decipher the trajectory of the story in time to avoid a disastrous ending. The great majority of experts in the field believe that current evidence definitively identifies humankind as the story's antagonist. The movie, of course, is left unfinished and has alternate endings. It leaves viewers wondering how the story will end.

Anticipating the outcome of the story is difficult. Prediction of the future is constrained by the limitations of scientific knowledge, the complexity of the climate system, uncertain population growth, an interconnected global economy, advances in technology, and changes in politics and policies.

Given these uncertainties, conclusions that scientists reach on future changes in climate are expressed in terms of probabilities and risks.

How we should proceed? Can climate projections inform us regarding what actions, if any, should be taken to reduce risks and impacts of climate change? How do we weigh the costs of action against the costs of inaction? Potential routes to tackle this dilemma are addressed in subsequent chapters.

Notes

1. Another difficulty in the creation of accurate climate models is the uncertainty inherent in the Earth's climate. Emanuel explains: "The amount of uncertainty in such [climate] projections can be estimated to some extent by comparing forecasts made by many different models" (Emanuel 2012, 46). He adds, "This exercise has been repeated using many different climate models, with the same qualitative result: one cannot accurately simulate the evolution of the climate over the last 30 years without accounting for the human input of sulfate aerosols and greenhouse gases. This is one (but by no means the only) important reason that almost all climate scientists today believe that man's influence on climate has emerged from the backgrounds of natural variability" (Emanuel 2012, 48–49).

2. Similarly, the fifth assessment report, released in 2013, stated, "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, sea level has risen, and the concentrations of greenhouse gases have increased" (IPCC 2013, 2).

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