1.1 Chapter Summary

Climate change is a result of global warming, a genuine phenomenon about which there is no significant debate within the scientific community. Rather, scientists debate the questions “How sensitive is climate to greenhouse gas buildup?” and “What will climate change look like regionally and locally?”

There is abundant, convincing, and reproducible scientific evidence that the increase in Earth’s surface temperature is having measurable impacts on human communities and natural environments: glaciers are melting; spring is arriving earlier; wildfires are becoming more frequent and intense; and ocean acidification is altering the marine ecosystems.

LEARNING OBJECTIVE

Since modern measurements began in 1880, Earth’s global mean surface temperature has increased approximately 1.1°C (1.8°F). Called global warming, this is caused by the accumulation of heat-trapping gases in the atmosphere that are produced when we burn coal, natural gas, and oil for energy. Deforestation and large-scale animal farming also produce these gases (called greenhouse gases). As a consequence of global warming, scientists have observed widespread climate change, which in turn is causing significant changes to Earth’s environments and ecosystems. Some changes are so dramatic that they are considered dangerous, and continued warming constitutes a global crisis that threatens human well-being, the health of the oceans and land-based ecosystems, and the very sustainability of Planet Earth.

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2 Greenhouse gases are heat-trapping gases in the atmosphere that raise the temperature. The higher temperature is known as the “greenhouse effect.” The natural greenhouse effect has made Earth livable, as without it the average temperature would be below freezing. However, every day, humans add huge quantities of greenhouse gases to the atmosphere, and the greenhouse effect has become amplified. This anthropogenic greenhouse effect is changing Earth in dangerous and unsustainable ways.

Chapter 1 Evidence of Climate Change

coming earlier; the tropics are expanding; sea level is rising; the global water cycle is amplified; storms are more intense and last longer; ecosystems are shifting, and plants and animals are experiencing local extinction; atmospheric and oceanic circulation are changing; the ocean is turning acidic and anoxic; drought, flooding, and other types of extreme weather are more common; heat waves kill thousands more people each year than historically; tropical diseases are spreading; food is more expensive; and insured losses have tripled.

These and many other observations document that Earth’s surface, which has always sustained humanity, is rapidly changing in dangerous and expensive ways. This is the result of global warming caused by human release of greenhouse gases into the atmosphere; a phenomenon known as anthropogenic climate change.

Climate change threatens all forms of life on this planet and raises the question “How will the human socio-economic framework change in response to climate change?”

In this chapter, you will learn the following:

- Human activities have caused levels of the heat-trapping gas carbon dioxide and other greenhouse gases to increase in the atmosphere.
- Humans are now manipulating global climate more rapidly than any geological analog other than a large extraterrestrial impact, leaving us with no natural guidelines on which to base predictions for how climate change will affect the world in coming years.
- In over 140 years of observations, increases in Earth’s surface temperature are setting new records every few years with record highs far outpacing record lows.
- Excess heat in the atmosphere is changing ecosystems, weather patterns, and other climate-dependent aspects of Earth’s surface.
- A number of natural processes cause variability in Earth’s climate—volcanic eruptions, the El Niño Southern Oscillation, variations in the Sun, changes in ocean circulation, and others. In recent decades, their net effect has been to cool the climate and thus do not account for observed rapid warming.
- If global warming continues at its current rate, Earth will be increasingly characterized by more abnormally hot days and nights; fewer cold days and nights; more frequent and severe droughts, hurricanes, and cold-season storms; a decrease in glaciers and ice sheets; erosion and flooding of coastal areas; and other effects capable of displacing large portions of the human population.
- All levels of the ocean are growing hotter, more acidic, and anoxic. These effects severely stress marine ecosystems.
- Leading research centers at universities, government offices, and independent institutions conduct scientific investigations and publish their results in peer-reviewed, critically evaluated journals and reports. The great majority of these are credible, unbiased, and abundant sources of information about climate change.
- Certain media sources that report on climate change are not credible as they seek to generate controversy through misinformation rather than report the facts about climate change.
- The Intergovernmental Panel on Climate Change (IPCC) releases special reports on topics relevant to the implementation of the United Nations Framework Convention on Climate Change, an international treaty that acknowledges the reality of harmful climate change.
- Certain “human fingerprints” on the climate system confirm that humans are the cause of global warming.

1.2 Introduction

Earth’s climate has always been restless, influenced by massive volcanic eruptions, extraterrestrial impacts, weathering mountain ranges, changes in Earth’s orientation to the Sun, variations in solar output, the El Niño Southern Oscillation (ENSO), shifts in ocean circulation and heat storage, and others. Some of these natural phenomena cause short-term climate variability (e.g., ENSO), and some are capable of causing global climate to change in dramatic, long-term, and profound ways (e.g., extraterrestrial impacts). These causes of climate change are intensively studied and, to this day, have yet to yield all of their secrets.

Modern climate change, however, does not fit natural history; in the past half-century, the rate and extent of climate change have been nothing short of astonishing. In fact, natural processes today have the net effect of cooling the climate, yet anthropogenic warming far outweighs their

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Footnotes:

1 Local extinction occurs when plants and animals are no longer found in their natural location.


8 Climate variability refers to short-term (months to decades) climate processes that occur at the same time that there is long-term (decades to centuries) climate change. Individual volcanic eruptions, El Niño and La Niña events, and multidecadal redistribution of heat in the oceans are examples. Climate variability is an important field of study in order to improve understanding of how short-term climate variations influence and interact with long-term climate change. Such studies help clarify the characteristics of long-term changes in climate, as well as how short-term variability is changing as a result. An example of the study of climate variability is the analysis of Pacific sea-level changes published by Hamilton, B. D., et al. (2016) An ongoing shift in Pacific Ocean sea level, J. Geophys. Res. Oceans, 121, 5084–5097, DOI:10.1002/2016JC011815.

influence. Around the world, ice is melting, seas are rising, local plant and animal extinctions cripple ecosystems, and record-setting storms rake the land and sea. Despite extensive research by thousands of scientists, no known natural process accounts for these extraordinary events.

1.2.1 The Greenhouse Effect

Yet an obvious culprit is well known; humans have been treating the atmosphere like an open sewer. For over a century, we have spewed industrial exhausts of carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and various fluorinated gases into the air as if it had infinite capacity to absorb these pollutants without negative effect. Simultaneously, we have deforested wide tracts of the planet that were effective at storing carbon dioxide and developed concentrated animal farming operations (CAFO) that emit massive quantities of methane.

These gases have a special property; they trap heat that comes off Earth’s surface after it has been warmed by the Sun. The more of these greenhouse gases there are in the atmosphere, the more heat is trapped and the hotter the air becomes. This is analogous to continuously adding blankets to your bed to capture your body heat and stay warm while you sleep, at some point you will add too many blankets and grow uncomfortably hot. Heat-trapping gases operate like heat-trapping blankets. Thus, Earth’s surface temperature rises in what is called the greenhouse effect. There is a natural greenhouse effect that allows the surface to be warmer than it would be otherwise (and support life). However, the human release of these same gases has created an enhanced greenhouse effect that is producing global warming, which in turn is causing climate change. (Figure 1.1).

1.2.2 Early Climate Science

Nearly two centuries of research underpin the modern science of climate change. Physicists in the 19th century realized that direct heating by the Sun did not sufficiently account for Earth’s surface temperature. Careful measurement revealed that once sunlight warms Earth’s surface, heat emitted back into the air by the land and the oceans can be trapped by water vapor and carbon dioxide and several other naturally occurring gases. In recognition of this process, the term greenhouse effect was coined at the beginning of the 20th century. The greenhouse effect is a natural process that warms Earth’s surface approximately 33 degrees Celsius (60 degrees Fahrenheit) more than it would otherwise be, allowing life as we know it on Earth.

Nineteenth-century scientists even predicted that burning coal and other carbon-rich fuels had the potential to double the amount of carbon dioxide in the air, trapping more heat and changing the climate. To conclude that modern climate change is a consequence of greenhouse gas emissions.

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gas accumulation is obvious; in fact, among scientists, this has been a well-documented, widely accepted conclusion for over 100 years.\textsuperscript{12}

Writing in the 1820s, French mathematician and physicist Jean-Baptiste Joseph Fourier (1768–1830) was the first to calculate that incoming solar radiation alone did not sufficiently account for Earth’s surface temperature. Although he ultimately favored interstellar radiation as the source of the additional warmth, he did consider the possibility that the atmosphere acts as an insulator of some kind. Today, this is widely recognized as the first proposal of the greenhouse effect, although Fourier never called it that.\textsuperscript{13}

French physicist Claude Servais Mathias Pouillet (1790–1868) expanded Fourier’s ideas and developed the first real mathematical treatment of Earth’s radiation budget. He speculated that water vapor and carbon dioxide trapped infrared (IR) radiation (heat) and therefore could account for the excess warmth identified by Fourier. However, there was no experimental proof that these gases absorbed heat.

The missing observations were provided by Irish physicist John Tyndall (1820–1893). At the time, early geologists were presenting evidence that Earth’s climate had recently emerged from a so-called ice age. Tyndall speculated that variations in carbon dioxide and water vapor might account for the changes in air temperature that would characterize an ice age (and the present interglacial). He provided the first measurements that these (and other) gases trapped heat, and he correctly concluded that water vapor was the principal gas controlling air temperature. Tyndall was the first to prove the existence of the greenhouse effect, although by his time, it was widely surmised.

Swedish scientist Svante August Arrhenius (1859–1927) was the first to use basic principles of physical chemistry to estimate the increase in Earth’s surface temperature based on the growth of carbon dioxide. He concluded that humanity’s burning of coal and oil was of such magnitude that it was capable of changing the air temperature, leading to global warming.\textsuperscript{14} He concluded that this warming would be strong enough to prevent the world from entering a new ice age; a good thing, in his opinion, as a warmer Earth would be needed to feed the rapidly increasing human population (Figure 1.2).

Guy Stewart Callendar (1897–1964) was an English engineer who compiled temperature measurements from the 19th and 20th centuries. He correlated these with contemporaneous measurements of atmospheric carbon dioxide concentrations. Callendar concluded that over the previous half-century, global land temperatures had increased. This, he concluded, could be explained as an effect of the increase in carbon dioxide. His estimates have been shown as remarkably accurate, especially as they were performed without the aid of a computer. However, his findings were met with skepticism at the time.

Charles David Keeling (1928–2005) was an American chemist who developed the first instrument to measure carbon dioxide in atmospheric samples. In 1958, he established an atmospheric monitoring base on Mauna Loa, Hawaii. By 1960, he had found that levels of carbon dioxide in the atmosphere rise and fall each year as plants, through photosynthesis and respiration, take up the gas in spring and summer and release it in fall and winter. In Keeling’s words, “We were witnessing for the first-time nature’s withdrawing CO\textsubscript{2} from the air for plant growth during summer and returning it each succeeding winter.”\textsuperscript{15}

Keeling’s measurements collected at Mauna Loa show a steady increase in mean atmospheric carbon dioxide concentration from about 315 parts per million (ppm) in 1958 to 411 ppm as of June 2018. This increase is due to the combustion of fossil fuels and has been accelerating in recent years (over the past decade the rate of increase is about

\textsuperscript{12} VIDEO: What we knew in ‘82, https://www.youtube.com/watch?v=OmpiuuBy-Is.
\textsuperscript{13} Who first coined the phrase “greenhouse effect?” Origin of the term is not clear, but an easy to read discussion of this question can be found here: http://www.easterbrook.ca/steve/2015/08/who-first-coined-the-term-greenhouse-effect/
\textsuperscript{15} Wikipedia: Svante Arrhenius; https://en.wikipedia.org/wiki/Svante_Arrhenius
\textsuperscript{16} The History of the Keeling Curve; https://scripps.ucsd.edu/programs/keelingcurve/2013/04/05/the-history-of-the-keeling-curve/
2 ppm per year). Since carbon dioxide is a greenhouse gas, this has significant implications for global warming. By the early 1970s, this curve was getting serious attention and played a key role in launching a government research program into the effect of rising CO$_2$ on climate. Since then, the rise has been relentless and shows a remarkably constant relationship with fossil-fuel burning based on the simple premise that 57 percent of fossil-fuel emissions remain airborne.

Now the longest continuous record of atmospheric carbon dioxide in the world, the Keeling Curve, has become an iconic symbol of both the value of long-term monitoring of natural systems and the powerful impact human activities have had on the planet (Figure 1.3).

1.2.3 Climate Change in Every Corner of Our Lives

The 2017 Fourth National Climate Assessment, Climate Science Special Report states:

\[ \ldots \text{“it is extremely likely that human influence has been the} \]
\[ \ldots \text{dominant cause of the observed warming since the mid-20th} \]

century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence.\[20\]

It is natural for all forms of life to change their environment, and humans are no exception. In fact, the human population is now of such size (almost 8 billion people), and technological sophistication that change is evident in many global systems.

For instance, humans affect the extent and health of the global forest,\[21\] global marine ecosystem,\[22\] global water quality and availability,\[23\] global sedimentation,\[24\] global reefs,\[25\]

\[\text{FIGURE 1.3 The Keeling Curve is a measurement of the concentration of carbon dioxide in the atmosphere made on the slopes of Hawaii’s Mauna Loa volcano since 1958. It is the longest-running such measurement in the world. Inset—the seasonal concentration of carbon dioxide in the atmosphere rises in the winter and falls in the summer. This is because of photosynthesis where plants accumulate carbon in the spring and summer when they’re active and release carbon back to the air in the fall and winter. Source: https://en.wikipedia.org/wiki/Keeling_Curve.}\]

\[\text{Data: NOAA/P. Tans} \]


\[\text{Keenan, R.J., et al. (2015) Dynamics of global forest area: Results from the FAO global forest resources assessment. Forest Ecology and Management, 352, 7 Sept., pp. 9–20: https://dx.doi.org/10.1016/j.foreco.2015.06.014} \]


\[\text{Heron, S.F., et al. (2016) Warming trends and bleaching stress of the world’s coral reefs 1985–2012, Scientific Reports, 6, 38402, DOI: 10.1038/srep38402} \]

\[\text{Notes from Wikipedia: https://en.wikipedia.org/wiki/Keeling_Curve} \]

\[\text{The History of the Keeling Curve.} \]
global river discharge\textsuperscript{26} (an estimated 36,000 dams interrupt the flow of nearly all of Earth’s river systems), global precipitation\textsuperscript{27} (storms and drought), and others. Accepting that climate is affected by human activities makes sense because it accounts most elegantly for the global phenomena scientists have observed over the past half-century (and, it has been suggested, much longer\textsuperscript{28}).

Because the cause of modern climate change is linked directly to human industrial activities and government policies,\textsuperscript{29} when we talk about the kinds of measures we could take to protect our children and ourselves from its worst effects, the discussion inevitably turns to jobs, taxes, government policies, human livelihoods, and personal choices. Unfortunately, when the discourse veers down these paths, the bright line around the science of climate change is blurred by political opinion, personal worldview, and individual beliefs.

Climate has even become political dogma\textsuperscript{30}, some assume that if you vote Democratic, you accept climate theory, if you vote Republican, you do not. Today in the United States, politicians filter their messages to appeal to their largest voter base.\textsuperscript{31} Climate change can also have religious connotations, “It is the height of human arrogance to think that we could control God’s creation,” is an oft-stated opinion.

It has been observed by social scientists that those with opinions at the extreme ends of the spectrum of views on climate change (i.e., deniers versus alarmists), have the loudest voices, while those in the middle with more moderate views don’t need to shout as much.

Researchers\textsuperscript{32} have categorized “Global warming’s six Americas.” Ranked from highest belief in global warming to lowest belief in global warming, these six (and their proportion of the U.S. adult population) are: Alarmed (18%), Concerned (33%), Cautious, (19%), Disengaged (12%), Doubtful (11%), and Dismissive (7%). Essentially, the American public does not speak with a single voice on the issue of global warming—they fall into six distinct populations.

Notably, the same study also found that the American public is almost unanimous on the positive value of sustainable energy, and they widely support investments in alternative energy. The alarmed and the dismissive alike endorse the idea of investing more resources into research on renewable energy. This informative revelation can be used to tailor public education efforts and develop strategies for how to best mobilize U.S. citizens to reduce the worst impacts of global warming. See the on this phenomenon.\textsuperscript{33}

Climate change enters the discussion of what to teach in schools, what is polite conversation, what kind of car to buy, the design of our buildings and cities, our source of electricity, and more. There are many examples of what is now known as the “climate debate.” The irony? That among mainstream scientists, there is no climate debate.

To paraphrase the National Research Council in their 2011 report, America’s Climate Choices,\textsuperscript{34} it is “settled fact” that the climate system is warming and much of this warming is very likely due to human activities. Why use the phrase “very likely?” Because volcanic eruptions, El Niño, and variations in the Sun’s energy also affect global temperature, but these have been intensely studied, and research indicates that their net influence on global climate has been to cool down Earth, but the global warming trend has been strong enough to overpower them.\textsuperscript{35} Climate does change naturally. See the box Spotlight on Climate Change, “Ice Ages and Interglacials.”

\textsuperscript{32} Yale Program on Climate Change Communication: http://climatecommunication.yale.edu/about/projects/global-warnings-six-americas/

\subsection*{1.3 Climate Change is Real and it is Dangerous}

Earth’s surface temperature is currently the warmest since modern record-keeping began in about 1880, and each of the last three decades has been successively warmer than any preceding decade since 1850 (Figure 1.5). According to the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), the average surface temperature of the ocean and land combined has risen about

\textsuperscript{33}VIDEO: Global Warnings Six Americas, http://climatecommunication.yale.edu/news-events/global-warnings-six-americas/
\textsuperscript{35} Foster, G. and Rahmstorf, S. (2011)
Climate Change is Real and it is Dangerous

Box 1.1 | Spotlight on Climate Change

Ice Ages and Interglacials
Over the past 500,000 years or so, Earth’s history has been characterized by natural swings in global climate, from extreme states of cold called ice ages, to warm periods (such as humanity has enjoyed for the past 10,000 years) called interglacials (Figure 1.4). The most recent of these was the transition, beginning about 18,000 years ago and lasting 8,000 to 10,000 years, from the end of the last ice age to the beginning of the current interglacial. This entailed worldwide warming of 6 to 10 degrees Celsius (10.8 to 18 degrees Fahrenheit). Notably, the temperature rise over the past century has been around 10 times faster than this natural rate of warming.

Repeating cycles of warm–cold–warm, known as interglacial cycles, occur in a regular rhythm approximately every 100,000 years. These cycles are guided by the amount of sunlight that reaches the Arctic due to oscillations in Earth’s tilt and orbit around the Sun. True to this timing, Earth’s surface temperature has been gently cooling over the past 10,000 years as it heads into the next ice age. However, because of modern global warming, humans have hijacked climate with greenhouse gases. Now, calculations indicate that we will delay the next ice age approximately 50,000 years because of the dramatic temperature changes associated with anthropogenic global warming.

Ice ages are characterized by the growth of massive continental ice sheets reaching across North America and northern Europe. At their maximum, these glaciers were over 4 km (2.5 mi) thick. Accompanying the spread of ice sheets was the dramatic expansion of glaciers located in mountain valleys (known as alpine glaciers), many of which expanded out of their valleys, coalesced with neighboring glaciers, and grew into thick icecaps that covered vast areas of mountainous territory.

The formation of all this ice required an immense reservoir of water, and the oceans were the obvious source. Evaporation from the oceans fed snow precipitation in the cold climate, and glaciers expanded around the world. As a result, sea level fell by as much as 130 m (426 ft), exposing shallow seafloor around the continents.

In several places, newly exposed continental shelves connected adjacent lands that were previously separated by water. These “land bridges” allowed early communities of humans and animals to migrate to new lands. If you had been alive during the last ice age, you could have walked on the exposed seafloor between Siberia and Alaska (a land bridge presumed to have aided the first peoples of the Americas), from France into England and from there to Ireland, and from Malaysia across Indonesia and on to Borneo. In many places, today’s shore is tens or even hundreds of kilometers from where it existed during the last ice age.

We currently live in an interglacial called the Holocene Epoch, which began about 10,000 years ago. The last ice age began approximately 75,000 years ago and culminated between 20,000 and 30,000 years ago. For approximately 50,000 years, the last ice age dominated Earth’s climate. It was a time of great changes to the landscape, as glaciers expanded and contracted, leaving myriad erosional and depositional glacial landforms.

![Figure 1.4](https://earth-observatory.nasa.gov/Features/GlobalWarming/page3.php)

**Figure 1.4** Recent geologic history is characterized by a series of ice ages and interglacials that occur on roughly 100,000-year cycles. In Chapter 4, we discuss in detail what causes interglacial cycles and how scientists study other forms of natural climate change.

Source: N. Hulbirt; Data: SkepticalScience.com.

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1.1 degrees Celsius (2.0 degrees Fahrenheit) over the past 136 years. 38 This period is now the warmest in the history of modern civilization. 39 Increased anthropogenic greenhouse gas emissions into the atmosphere drive this change. 40 We explore greenhouse gases more fully in Chapter 2.

Relative to the period of 1986–2005, Earth’s surface temperature is projected to rise another 0.3 to 4.8 degrees Celsius (0.5 to 8.6 degrees Fahrenheit) before the end of the 21st century, depending on the rate and amount of greenhouse gases that are released to the atmosphere. 41 The projected temperature rise makes it very likely that heat waves will occur more often and last longer, extreme precipitation events will become more intense and frequent in many regions, the ocean will continue to warm and acidify, and global mean sea level will rise.

While these temperature changes may appear to be small and not very serious, minor changes in the average surface temperature of the planet can translate to large and potentially dangerous shifts in climate and weather. As this chapter will show, the evidence is clear. Rising global temperatures are already accompanied by dangerous changes in surface conditions on Earth.

For instance, the planet’s oceans and glaciers have already experienced some big changes—oceans are warming and becoming more acidic as they absorb some of the excess carbon dioxide that we have dumped into the atmosphere, ice caps are melting, and sea levels are rising. As these and other changes become more pronounced in coming decades, they will present costly, daunting challenges to our society and our environment. 42

1.3.1 Earth Resources Are More Depleted Every Day

In his book Earth in Mind, 43 David Orr writes that on a typical day, we lose about 300 square km (116 sq. mi) of rainforest to logging (one acre per second), 186 square km (72 sq. mi) of land to encroaching deserts, and numerous species to extinction. Other sources tell us that in a day, the world’s human population increases by more than 200,000, 44 we add 100 million tons 45 of carbon dioxide to the atmosphere, and we burn an average of 84.4 million barrels of oil (1000 barrels per second 46). By the end of the day, Earth’s freshwater, soil, and ocean are more acidic. 47

59 Wuebbles et al. (2017)
its natural resources more depleted, and its temperature a little hotter.  

These unrelenting impacts to Earth’s ecosystems and natural resources have led researchers to conclude that our planet is perched on the edge of a tipping point, a planetary-scale critical transition resulting from human influence.  

Scientists are warning that human population growth, widespread destruction of natural ecosystems, and climate change are pushing Earth’s ecosystems and resources toward irreversible change.  

Toward the end of 2017, an astonishing 15,000 scientists joined together as coauthors issuing a dire warning to humanity. They reported that humans have pushed Earth’s ecosystems to their breaking point and are well on the way to ruining the planet. This letter follows an earlier warning that was issued 25 years earlier in 1992 from the Union of Concerned Scientists. The environmental impacts listed in that earlier warning included stratospheric ozone depletion, air and water pollution, the collapse of fisheries and loss of soil productivity, deforestation, species loss, and catastrophic global climate change caused by the burning of fossil fuels.

Global climate change leads the new letter’s list of planetary threats. Global average temperatures have risen by more than 0.5 degree Celsius (0.9 degree Fahrenheit) since 1992, and annual carbon dioxide emissions have increased by 62 percent. But climate change is not the only problem the world faces.

Access to freshwater has declined, as has the amount of forestland and the number of wild-caught fish (a marker of the health of global fisheries). The number of ocean dead zones has increased. The human population grew by a massive 2 billion, while the populations of all other mammals, reptiles, amphibians, and fish have declined by nearly 30 percent. The 2017 warning points to several negative environmental trends, including:

- A 26% reduction in the amount of freshwater available per capita
- A drop in the harvest of wild-caught fish, despite an increase in fishing effort
- A 75% increase in the number of ocean dead zones
- A loss of nearly 300 million acres of forestland, much of it converted for agricultural uses
- Continuing significant increases in global carbon emissions and average temperatures
- A 53% rise in human population
- A collective 29% reduction in the numbers of mammals, reptiles, amphibians, birds, and fish

The warning came with steps to reverse negative trends, but the authors suggest that it may take a groundswell of public pressure to convince political leaders to take the right corrective actions. Such activities could include establishing more terrestrial and marine reserves, strengthening enforcement of anti-poaching laws and restraints on wildlife trade, expanding family planning and educational programs for women, promoting a dietary shift toward plant-based foods, and massively adopting renewable energy and other “green” technologies.

1.3.2 National Academy of Sciences

Orr was not merely speculating. According to the U.S. National Academy of Sciences, it is “settled fact” that the Earth system is warming, and there is 90–99 percent probability that humans are the cause.

“Some scientific conclusions or theories have been so thoroughly examined and tested, and supported by so many independent observations and results, that their likelihood of subsequently being found to be wrong is vanishingly small. Such conclusions and theories are then regarded as settled facts. This is the case for the conclusions that the Earth system is warming and that much of this warming is very likely due to human activities.”

This quotation, published in 2011 by a panel of scientists convened by the U.S. National Academy of Sciences, is included in a set of five volumes collectively called America’s Climate Choices. The panel was compelled to conclude that “There is a strong, credible body of scientific evidence showing that climate change is occurring, is caused largely by human activities, and poses significant risks for a broad range of human and natural systems.”

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54 Biologists Say Half of All Species Could be Extinct by End of the Century: https://www.theguardian.com/environment/2017/feb/25/half-all-species-extinct-end-century-vatican-conference
55 VIDEO: James Hansen on Ice Sheets, https://www.youtube.com/watch?v=Vkn8_sfQgNk&time=25s
According to a joint publication\textsuperscript{57} by the British Royal Society and the U.S. National Academy, rigorous analysis of all data and lines of evidence shows that most of the observed global warming over the past 50 years or so cannot be explained by natural causes and instead requires a significant role for the influence of human activities.

Global warming causes climate change. Warming is a consequence of deforestation (\textbf{Figure 1.6}), industrial agriculture, manufacturing, transportation, and other human activities that increase the concentration of heat-trapping greenhouse gases in the atmosphere. Actions such as burning oil and coal\textsuperscript{58} release these gases to the atmosphere in quantities that have increased with the rise of the industrial age (and, as one respected climatologist proposes, since humans first domesticated animals and cleared land for farms beginning 8,000 years ago\textsuperscript{59}).

\textbf{Figure 1.6} In Brazil, the Amazon rainforest is cleared to make way for farming. Across the middle and top of the photo, taken by astronauts aboard the International Space Station, light land areas reveal the extent of deforestation. Brush and debris are burned, releasing their carbon to the atmosphere and forever destroying the natural ability of the rainforest to store carbon and counteract global warming.\textsuperscript{60}


\textsuperscript{57} U.S. National Academy of Sciences http://nas-sites.org/americasclimatechoices/events/a-discussion-on-climate-change-evidence-and-causes/
\textsuperscript{58} Called “fossil fuels” because coal is made from fossil plants, and oil is made of fossil marine algae.
\textsuperscript{59} William Ruddiman has proposed the “anthropogenic hypothesis.” It is built on ice core data and calculations of the Earth–Sun orbital geometry, suggesting that the relatively warm climate of the past several thousand years is unnatural and should instead have been characterized by cooling. Ruddiman proposes that through the production of excess methane and carbon dioxide, human agricultural practices took control of Earth’s climate as early as 5,000 to 8,000 years ago, Ruddiman (2003); Ruddiman, W.F. (2005) Cold climate during the closest stage 11 analog to recent millennia, Quaternary Science Reviews 24, 1111–1121; and Ruddiman, W.F. (2005) Plows, Plagues, and Petroleum: How Humans Took Control of Climate, Princeton, N.J., Princeton University Press.
\textsuperscript{60} VIDEO: Deforestation, https://www.nytimes.com/2017/02/24/business/energy-environment/deforestation-brazil-bolivia-south-america.html?_r=1

1.3.3 Climate Change Evidence

There is abundant, convincing, and reproducible scientific evidence that the increase in Earth’s surface temperature has measurable impacts on human communities and natural ecosystems. Scientists accept this as fact.

Consequently, research efforts center on questions such as: Is climate changing faster than anticipated? How is climate change affecting ecosystems, the weather, the ocean, and Earth’s cryosphere? What are the best ways to predict future impacts of climate change?\textsuperscript{61}

- In September 2016, the global atmospheric carbon dioxide concentration permanently passed 400 parts per million (ppm\textsuperscript{62}), growing at an average annual rate of about 2 ppm, more than twice the growth rate during the 1990s.\textsuperscript{63} Carbon dioxide in the atmosphere is now rising faster than it has in hundreds of thousands of years.\textsuperscript{64} This concentration is the highest since the Miocene Epoch (15 million years ago),\textsuperscript{65} when sea level is estimated to have been 25 to 40 m (82 to 131 ft) higher and global temperature 3 to 6°C (5 to 10°F) warmer than current temperatures.
- Today’s release of planet-warming carbon dioxide is about ten times faster than the most rapid event of any time in at least the past 66 million years, when an asteroid impact killed the dinosaurs. Richard Zeebe and colleagues\textsuperscript{66} arrived at this conclusion when they compared the rate of carbon released (less than approximately 1.1 trillion kilograms of carbon per year) during the Paleocene–Eocene Thermal Maximum (PETM), a major warming episode 56 million years ago, to the present rate of carbon released by industrial activities (approximately 10 trillion kilograms of carbon per year). Global climate then was

\textsuperscript{62} The abbreviation “ppm” means parts per million. It is a measurement of abundance (or concentration) the same way that “per cent” means parts per hundred. In this case ppm means molecules of CO\textsubscript{2} per million molecules of air.
\textsuperscript{64} Kerr (2009)
\textsuperscript{65} The annual growth rate of atmospheric carbon dioxide measured at NOAA’s Mauna Loa Observatory in Hawaii jumped by 3.05 ppm during 2015, the largest year-to-year increase in 56 years of monitoring. In another first, 2015 was the fourth consecutive year that CO\textsubscript{2} grew more than 2 ppm, said Pieter Tans, lead scientist of NOAA’s Global Greenhouse Gas Reference Network. “Carbon dioxide levels are increasing faster than any time in at least the past 66 million years, when an asteroid impact killed the dinosaurs. Richard Zeebe and colleagues\textsuperscript{66} arrived at this conclusion when they compared the rate of carbon released (less than approximately 1.1 trillion kilograms of carbon per year) during the Paleocene–Eocene Thermal Maximum (PETM), a major warming episode 56 million years ago, to the present rate of carbon released by industrial activities (approximately 10 trillion kilograms of carbon per year). Global climate then was

\textsuperscript{66} Tripati, A.K., et al. (2009) Coupling of CO\textsubscript{2} and ice sheet stability over major climate transitions of the last 20 million years, Science, 326(5958), 1394–1397, http://www.sciencemag.org/cgi/content/abstract/1178296
\textsuperscript{67} Zeebe, R.E., et al. (2016) Anthropogenic carbon release rate unprecedented during the past 66 million years, Nature Geoscience, DOI: 10.1038/ngeo2681
more than 8 degrees Celsius (14.4 degrees Fahrenheit) warmer than current temperatures. There are various hypotheses as to what caused the PETM including a comet impact, degassing of CO₂ from a massive magma body, changes in ocean circulation, extensive volcanic activity, and release of methane from frozen seafloor sediments. Regardless of the cause, Zeebe’s calculations indicate that humans are now manipulating global climate more rapidly than any geological analog other than a large extraterrestrial impact, leaving us with no natural guidelines on which to base predictions for how climate change will affect the world in coming years.68

* In 2014, the average temperature on Earth’s surface was the hottest in the modern era. The year 2015 exceeded that by 20 percent, a record-setting increase never before seen. In 2016, the temperature was boosted approximately 0.12 degrees Celsius (0.2 degrees Fahrenheit) by a strong El Niño (we discuss the El Niño Southern Oscillation, or ENSO, in more detail in Chapter 5) and set yet another new record.69 Overall, Earth’s average surface temperature has increased approximately 1.0°C (1.8°F) since modern record-keeping began in 1880. According to NASA, this change is driven by increased carbon dioxide and other greenhouse gas emissions into the atmosphere.70

* Overall, the global annual temperature has increased at an average rate of 0.07 degrees Celsius (0.13 degrees Fahrenheit) per decade since 1880 and at an average rate of 0.2 degrees Celsius (0.36 degrees Fahrenheit) per decade since 1970.71

The years 1998 and 2005 set records for warmth. In 2008, however, global mean temperature dropped, returning to temperatures not seen since the mid-1990s (although 2008 was, nonetheless, the ninth warmest year on record at the time). A graph of annual temperatures from 1998 to 2013 looked as if global warming had stopped when, in fact, average annual global temperature over the period still had a positive trend. Nevertheless, the drop in temperature from 2005 to 2008 influenced national attitudes and a trend of “global cooling” was reported in some media. However, mistaking short-term climate variability (year-to-year changes in temperature) for long-term trends (climate change) is a fundamental error.

By 2009, global temperature was on the upswing again, and it tied with a cluster of years—1998, 2002, 2003, 2006, and 2007—as the second warmest year on record. December 2009 also marked the end of the warmest decade with a warming trend over the previous 30 years of 0.2 degrees Celsius (0.36 degrees Fahrenheit) per decade.72 Typical of the history now established, subsequent years displayed a high degree of variability: 2010 tied for the warmest year on record; 2011 ranked as ninth warmest year; 2012 replaced 2011 as ninth warmest year; and 2013 tied with 2009 and 2006 for seventh warmest year.

However, the years 2014, 2015, and 2016 all, in turn, outstripped each other for warmest years on the modern record. Earth’s surface temperature had ended a 16 years-long period of variability and entered a phase of fearsome warming.

Three record-setting years in a row is unprecedented in the 140-year-long modern history of global climate. Temperatures in 2016 not only set an annual record, but January through May and July through September (8 out of 12 months) were the warmest on record for those respective months. October and November were the second warmest of those months, just behind records set in 2015.73

Earth’s global surface temperatures in 2017 ranked as the second warmest since 1880. Continuing the planet’s long-term warming trend, globally averaged temperatures in 2017 were 0.90 degrees Celsius (1.62 degrees Fahrenheit) warmer than the 1951–1980 mean, according to scientists at NASA’s Goddard Institute for Space Studies (GISS) in New York.74 That is second only to global temperatures in 2016.

Scientists do not expect global warming to be expressed as a smooth annual rise in average atmospheric temperature from one year to the next. They understand that short-term climate processes (e.g., the El Niño Southern Oscillation, the sunspot cycle, volcanic eruptions) dominate year-to-year temperatures75 and that it does not get warmer everywhere at the same time. Similar to the rise in stock market value since the 1970s, climate is taking a bumpy ride of ups and downs as it undergoes a long-term increase in global surface temperature.

In the same way, scientists do not take every snowstorm and cool day as evidence that global warming is not a looming issue or that it does not exist at all. In fact, anthropogenic climate change is responsible for record-setting snowstorms and cold snaps through what is known as Arctic amplification, the rapid warming taking place in the Arctic, which is three times faster than the global average. We explain this linkage of Arctic amplification to extreme winter events in Chapter 3.

On the contrary, scientists recognize that global warming is a “noisy” process that requires analysis of both short-term events and the long-term trends. By 2009, studies emerged that supported this view. In a blind test, the Associated Press gave prominent statisticians global temperature data

68 Mashable http://mashable.com/2016/03/21/CO2-fastest-66-million-years/#SppChQyuaqN
70 NASA: https://www.giss.nasa.gov/research/news/20170118/
71 NOAA: https://www.ncdc.noaa.gov/sotc/global/201613
72 NASA: https://www.giss.nasa.gov/research/news/20100121/
without identifying its source or what the numbers represented. The statisticians rejected global cooling because they recognized that short-term statistical variability does not represent a long-term trend.\(^\text{76}\) Also, the U.S. National Climate Data Center published peer-reviewed research\(^\text{77}\) reporting that climate history since the 1970s reveals many episodes when the average temperature of the atmosphere temporarily stopped rising, and even reversed its upward climb, but that strong net warming over the entire period is indisputable.

### 1.4 The Earth System is Changing

From soil at the equator to ice at the poles, the circulation of heat through Earth’s atmosphere and oceans links the planet’s living organisms and environments.\(^\text{78}\) Certain global processes connect the poles and tropics, deserts and forests, continents and oceans even though Earth is 40,075 km (24,901 mi) in circumference and has a surface area of 509,600,000 square km (196,757,000 sq. mi). This vast area is characterized chiefly by mixing of the atmosphere and ocean, the water cycle, seasonal heating and cooling, and more.

Global warming changes cause to these processes on the scale of the whole Earth. Detailed analysis of ice core records of climate over the past 20,000 years reveals that today’s changes in climate are unique over that entire period; there is no “natural process” that can explain today’s warming.\(^\text{79}\)

#### 1.4.1 Irreversible Change

Earth is not an unchanging ball of rock hurtling through space. Energy from within and without alters it. For example, heat diffuses upward from the core through the mantle, Earth’s thickest layer, causing rock in the mantle to plastically flow and migrate. As heat moves through the crust, the outermost layer, it drives plate tectonics and causes volcanism.\(^\text{80}\) Heat also arrives from the Sun. As this heat circulates through the atmosphere and oceans, and is carried by ocean and air currents around the planet, it influences Earth’s weather and climate.

These processes make Earth dynamic and cause it to constantly change on long and short timescales, and it has been this way, in various forms, throughout its 4.6 billion-year history. For most of that history, natural processes have controlled those changes, and many of them have been enormous (e.g., the collision of continents driven by plate tectonics; the increasing diversity of living forms; the massive extinctions that characterize the fossil record). The natural processes that cause global climate change include plate tectonics, volcanic eruptions, extraterrestrial impacts, and variations in Earth’s orbit (which we study in Chapter 4). Human activities can also cause global climate change.

On modern Earth, human activities have indeed caused global changes in land use, air and water quality, and the abundance of natural resources,\(^\text{81}\) particularly over the past two centuries. There is scientific consensus that human activities are altering Earth’s climate, largely owing to increasing levels of the heat-trapping gas carbon dioxide and other greenhouse gases (Figure 1.7).

Because it can reside in the atmosphere for more than 1,000 years,\(^\text{84}\) carbon dioxide is the most dangerous greenhouse gas. It is released when we burn fossil fuels, sources of energy provided by burning fossil carbon, such as petroleum (fossil marine algae) and coal (fossil continental wetland plants).

A study by NOAA\(^\text{85}\) concluded that climate change is largely irreversible for the next 1,000 years because of the long lifetime of CO\(_2\) in the atmosphere. As a result, at higher levels of CO\(_2\) (450 to 600 ppm), sea-level rise, changes in rainfall, severe weather events, and other consequences of global warming will come to permanently characterize the planet’s surface.

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\(^{76}\) Borenstein, S., Statisticians Reject Global Cooling, Associated Press, October 26, 2009.


\(^{78}\) VIDEO: The Ocean, A Driving Force for Weather and Heat, https://www.youtube.com/watch?v=6vgvTeuoDWY

\(^{79}\) Bjorck, S. (2011) Current global warming appears anomalous in relation to the climate of the last 20,000 years, Climate Research 48(1), 5, DOI: 10.3354/cr00873

\(^{80}\) VIDEO: Plate Tectonics, https://www.youtube.com/watch?v=Xzpk9110Lyw

\(^{81}\) According to the 2016 Edition of the National Footprint Accounts, humanity demanded the resources and services of 1.6 planets in 2016; such demand has increased over 2.5 times since 1961. This situation, in which total demand for ecological goods and services exceeds the available supply for a given location, is known as “overshoot.” Global overshoot indicates that stocks of ecological capital may be depleting, and/or that waste is accumulating, beyond Earth’s capacity to sustain a healthy ecosystem. It means that we are borrowing from the future to live today. Global Footprint Network, http://www.footprintnetwork.org/en/index.php/GFN/page/at_a_glance/


\(^{85}\) Solomon et al. (2009)
1.4.2 Observed Impacts

Changes in precipitation (rain and snowfall), the source of our drinking water, cause of floods, and the crucial factor governing the health of critical ecosystems that provide us with natural resources, are of special concern to humanity. Studies document that global warming directly influences precipitation because the water-holding capacity of air increases by about 7 percent for each 1 degree Celsius (1.8 degrees Fahrenheit) of warming. Thus, storms that are provided with more moisture produce more-extreme precipitation events. Warmer air also results in greater evaporation that dries Earth’s surface, increasing the intensity and duration of drought. Global warming is producing a world that is drier, yet, ironically, prone to greater flooding.

Because warming is producing only modest changes in winds, generalized precipitation patterns do not shift their location much, and thus, wet areas are becoming wetter and dry areas are becoming drier. Globally, a warmer atmosphere produces more rainfall instead of snow, and winter snowpack develops later and melts earlier. This increases runoff in late winter and early spring, raising the risk of flooding (Figure 1.8) and extending the duration and intensity of summer drought. Farmers, communities, and government agencies responsible for public safety and health all find it challenging to adapt to this new pattern.

Simultaneously there are climate processes related to global warming that increase extreme winter weather. For instance, on the eastern seaboard of the United States, the warmer water of the Gulf Stream provides additional water vapor that can produce heavier snowfall during winter storms (nor’easters). As cold air masses from the north-central United States collide with the increased moisture off the warmer Atlantic, some record-setting snowstorms have occurred. Similarly, among the snow belts along the Great Lakes, warmer winters are keeping more of the lake surfaces ice-free, promoting evaporation and heavier snows downwind of Lakes Erie, Ontario, and Michigan particularly.

These phenomena may lead students to say “How can Earth be warming when it’s snowing more in winter?” The answer lies with paying attention to the details of Earth’s weather systems and knowing how warmer air influences climate patterns in ways that are scientifically consistent. In Chapter 3, we introduce the role of global warming in altering the Polar Jet Stream and how this also leads to increased extreme weather in the Northern Hemisphere, including more heat waves, and record-setting cold events.

Many studies indicate that the climate change observed during the 20th and early 21st centuries is due to a combination of changes in solar radiation, volcanic activity, land use, and increases in atmospheric greenhouse gases. Of these, greenhouse gases are the dominant long-term influence, and they are causing the lower atmosphere, the air closest to Earth, to warm. This excess heat is causing dramatic changes in ecosystems, weather patterns, and

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Evidence of Climate Change

Other climate-dependent aspects of Earth’s surface. These changes include the following.

1. Carbon dioxide levels in the air have passed 400 ppm compared to a natural level of 280 ppm—an increase of over 40%. This is the highest level in millions of years.

2. Today, release of planet-warming carbon dioxide is ten times faster than the most rapid event in the past 66 million years, when an asteroid impact killed the dinosaurs.

3. Humans are causing the climate to change 170 times faster than natural forces.

4. Global temperature has risen approximately 1°C (1.8°F) from the late 19th Century.

5. The likely range of global temperature increase is 2.0–4.9°C, with median 3.2°C (5.76°F) and a 5% (1%) chance that it will be less than 2°C (1.5°C).

6. The last time it was this warm was during the last interglacial (ca. 125,000 years ago) when global mean sea level was 6.6 m (20 ft) above present.

7. Atmospheric humidity is rising.

8. The global water cycle has accelerated.

9. Air temperature over the oceans is rising.

10. Greenland is losing ~286 billion tons of ice annually, Antarctica is losing ~159 tons, and alpine glaciers are losing over 200 billion tons of ice annually.

11. The west Antarctic ice sheet is in “unstoppable” collapse.

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96 Hoffman, J.S., et al. (2017) Regional and global sea surface temperatures during the last interglaciation, Science, 355(6322), 276–279, DOI: 10.1126/science.aai8464
98 Durack et al. (2012)
100 Radić, V. and Hock, R. (2011) Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise, Nature Geoscience, 4, 91–94, DOI: 10.1038/ngeo1052
12. Glaciers worldwide are melting.104
13. Melting on Greenland and Antarctica has accelerated.105
14. Cloud cover over Greenland is decreasing at about 0.9% per year. Each 1% of decrease drives an additional 27±13 billion tons of ice melt each year.106
15. Alpine glaciers have shrunk to their lowest levels in 120 years and are wasting two times faster than they did in the period 1901–1950, three times faster than they did in 1851–1900, and four times faster than they did 1800–1850.107
16. Continental ice sheets are shrinking.108
17. Arctic sea ice is shrinking as a result of global warming.109
18. Winter Arctic sea ice was the lowest on record in 2017.110
19. In the Arctic, average surface air temperature for the year ending September 2016 was the highest since 1900, and new monthly record highs were recorded for January, February, October, and November 2016.111
20. Rapid warming in the Arctic is causing the jet stream to slow and develop large planetary waves.112
21. Regions of Earth where water is frozen for at least 1 month each year are shrinking with impacts on related ecosystems.113
22. In North America, spring snow cover extent in the Arctic was the lowest in the satellite record, which started in 1967.114
23. Extreme warm events in winter are much more prevalent than cold events.115

104 Radić and Hock (2011)
107 Zemp et al. (2015)
108 Rignot et al. (2011)
110 See: http://nside.org/arcticseaicenews/
114 Arctic Report Card (2016)
24. Snow cover is shrinking.116
25. The southern boundary of Northern Hemisphere permafrost is retreating poleward.117
26. Large parts of permafrost in northwest Canada are slumping and disintegrating into running water. Similar large-scale landscape changes are evident across the Arctic including in Alaska, Siberia, and Scandinavia.118
27. Tree lines are shifting poleward and to higher elevations.119
28. Spring is coming sooner to some plant species in the Arctic while other species are delaying their emergence amid warm winters. The changes are associated with diminishing sea ice.120
29. Air temperature over land is rising.121
30. The global percentage of land area in drought has increased about 10%.122
31. The global occurrence of extreme land area in drought has increased about 10%.123
32. Heavy downpours are more intense and frequent.124
33. Extreme weather events are more frequent.125
34. 0.5°C of global warming has been enough to increase heat waves and heavy rains in many regions of the planet.126
35. Storm tracks are shifting poleward.127
36. The number of weather disasters is up 14% since 1995–2004 and has doubled since 1985–1994.128
37. In Australia, record-setting hot days outnumber record-setting cold days by a factor of 12 to 1.\textsuperscript{129}
38. Extreme heat waves are projected to cover double the amount of global land by 2020 and quadruple by 2040, regardless of future emission trends.\textsuperscript{130}
39. New records continue to be set for warm temperature extremes. For instance, in the United States during February, 2017, there were 3,146 record highs set compared to only 27 record lows, a ratio of 116 to 1.\textsuperscript{131}
40. Nine of the ten deadliest heat waves have occurred since 2000, causing 128,885 deaths around the world.\textsuperscript{132}
41. Nearly, one-third of the world’s population is now exposed to climatic conditions that produce deadly heat waves.\textsuperscript{133}
42. If global temperatures rise 2°C (3.6°F), the combined effect of heat and humidity will turn summer into one long heat wave. Temperature will exceed 104°F every year in many parts of Asia, Australia, Northern Africa, South and North America.\textsuperscript{134}
43. If global temperatures rise 4°C (7.2°F), a new “super-heatwave” will appear with temperatures peaking at above 131°F making large parts of the planet unlivable including densely populated areas such as the U.S. east coast, coastal China, large parts of India and South America.\textsuperscript{135}
44. Aridification will emerge over about 20% to 30% of the world’s land surface by the time global mean temperature change reaches 2°C.\textsuperscript{136}
45. Drought severity has been increasing across the Mediterranean, southern Africa, and the eastern coast of Australia over the course of the 20th century, while semiarid areas of Mexico, Brazil, southern Africa, and Australia have encountered desertification for some time as the world has warmed.\textsuperscript{137}
46. Global warming has reached at least 1°C (1.8°F) above the natural background. The last time it was this warm was during the last interglacial (ca. 125,000 years ago)\textsuperscript{138} when global mean sea level was approximately 6.6 m (20 ft) above the present.\textsuperscript{139}
47. Global wind speed has accelerated.\textsuperscript{140}
48. Spring is coming earlier.\textsuperscript{141}
49. Warmer winters with less snow have resulted in a longer lag time between spring events and a more protracted vernal window (the transition from winter to spring).\textsuperscript{142}
50. Plants are leafing out and blooming earlier each year.\textsuperscript{143}
51. Climate-related local extinctions have already occurred in hundreds of species, including 47% of 976 species surveyed.\textsuperscript{144}
52. Plant and animal extinctions, already widespread, are projected to increase from twofold to fivefold in the coming decades.\textsuperscript{145}
53. Rising CO\textsubscript{2} decreases the nutrient and protein content of wheat, leading to a 15% decline in yield by mid-century.\textsuperscript{146}

\textsuperscript{131} Climate Central.org: http://www.climatecentral.org/news/record-high-temperature-february-2011
\textsuperscript{133} Mora, C., et al. (2017) Global risk of deadly heat. Nature Climate Change, DOI: 10.1038/nclimate3322
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54. By 2050, climate change will lead to per-person reductions of 3% in global food availability, 4% in fruit and vegetable consumption, and 0.7% in red meat consumption. These changes will be associated with 529,000 climate-related deaths worldwide.147

55. Without changes to policy and improvements to technology, food productivity in 2050 could look like it did in 1980 because, at present rates of innovation, new technologies won’t be able to keep up with the damage caused by climate change in major growing regions.148

56. Certain groups of Americans—including children, elders, the sick, and the poor—are most likely to be harmed by climate change.149

57. Climate change is harming human health now. These harms include heat-related illness, worsening chronic illnesses, injuries and deaths from dangerous weather events, infectious diseases spread by mosquitoes and ticks, illnesses from contaminated food and water, and mental health problems.150

58. The lower atmosphere (troposphere) is warming.151

59. The tropics have expanded.152

60. Species are migrating poleward and to higher elevations.153

61. Atmospheric humidity is rising.154

62. The global water cycle has accelerated.155

63. Air temperature over the oceans is rising.156

64. Sea surface temperature is rising.157

65. The oceans are warming rapidly.158

66. Sea level is rising, and the rate of rise has accelerated.159

67. Today, global mean sea level is rising three times faster than it was in the 20th century.160

68. Between 1993 and 2014, the rate of global mean sea-level rise increased 50% with the contribution from melting of the Greenland Ice Sheet rising from 5% in 1993 to 25% in 2014.161

69. We have already committed to a long-term future sea level 1.3 to 1.9 m (4.3 to 6.2 ft) higher than today and are adding about 0.32 m/decade (1 ft/decade) to the total: ten times the rate of observed contemporary sea-level rise.162

70. Over 90% of the heat trapped by greenhouse gases since the 1970s has been absorbed by the oceans, and today, the oceans absorb heat at twice the rate they did only 18 years ago.163

71. The world’s oceans have warmed at twice the rate of previous decades and the extra heat has reached deeper waters.164, 165

72. Sea surface temperatures have increased in areas of tropical cyclone genesis suggesting a connection with strengthened storminess.166


155 Durack et al. (2012)


158 Wang, G., et al. (2017) Consensuses and discrepancies of basin-scale ocean heat content changes in different ocean analyses, Climate Dynamics. DOI: 10.1007/s00382-017-3751-5


73. Oxygen levels in the ocean have declined by 2% over the past five decades because of global warming, probably causing habitat loss for many fish and invertebrate species.  

74. Marine ecosystems can take thousands, rather than hundreds, of years to recover from climate-related upheavals.  

75. The world’s richest areas for marine biodiversity are also those areas mostly affected by both climate change and industrial fishing.  

76. The Atlantic Meridional Overturning Circulation has decreased 20%. The North Atlantic has the coldest water in 100 years of observations.  

77. The number of coral reefs impacted by bleaching has tripled over the period 1985–2012.  

78. By 2050, more than 98% of coral reefs will be afflicted by bleaching-level thermal stress each year.  

79. Scientists have concluded that once seas are hot enough for long enough, nothing can protect coral reefs. The only hope for securing a future for coral reefs is urgent and rapid action to reduce global warming.  

80. Average pH of ocean water fell from 8.21 to 8.10, a 30% increase in acidity. Ocean water is more acidic from dissolved CO₂, which is negatively affecting marine organisms.  

81. Marine ecosystems are under extreme stress.  

82. Production of oxygen by photosynthetic marine algae is threatened at higher temperatures.  

83. Extreme weather is increasing.  

84. Global warming is changing life on Earth on a global scale.  

85. There is only a 5% chance of avoiding dangerous global warming of 2°C (3.6°F).  

1.4.3 U.S. Global Change Research Program

How will all these dramatic and overwhelmingly negative changes play out in a future characterized by continued global warming? This question has been at the root of much of the research being conducted by climate scientists in recent years. For instance, in a report produced by the U.S. Global Change Research Program, a combined effort of more than a dozen government science agencies, researchers found the following.

- In the future, abnormally hot days and nights and heat waves are very likely to become more common.
- Cold days and cold nights are very likely to become much less common. The number of days with frost is very likely to decrease.
- Future sea ice extent will continue to decrease and could even disappear entirely in the Arctic Ocean in summer in coming decades. Sea ice loss has increased coastal erosion in Arctic Alaska and Canada because of increased exposure of the coastline to wave action. It has disrupted long-standing ecosystem processes such as predator–prey relationships, mating, seasonal migrations, forage and overall food availability, and prevalence of pests, diseases, and other health and mortality factors.
- Future precipitation is likely to be less frequent but more intense, and precipitation extremes are very likely to increase.
- Future droughts are likely to become more frequent and severe in some regions (e.g., U.S. Southwest, Mexico), leading to a greater need to respond to reduced water supplies, increased wildfires, and various ecological impacts.
- Future hurricanes in the North Atlantic and North Pacific are likely to have increased rainfall and wind speeds; for each 1°C (1.8°F) increase in tropical
sea-surface temperatures, rainfall rates will increase by 6% to 18% and wind speeds of the strongest hurricanes will increase by 1% to 8%.

• In the future, strong cold-season storms in both the Atlantic and Pacific are likely to be more frequent, with stronger winds and more extreme wave heights.

Climate change has already transformed our planet. Air temperatures have risen and, as a result, heat waves and drought are more common. Storms have increased in frequency and intensity, seasons have shifted, and the ranges of plant and animal life have moved. The glaciers are melting, global sea level is rising and accelerating, and the temperature of the oceans has increased. Climate change is rapidly altering the lands and waters we depend on for survival, and the cause is the buildup of greenhouse gases produced by human activities.

During the summer of 2012, following the warmest spring on record, the average temperature of the continental United States was 2.5 degrees Celsius (4.5 degrees Fahrenheit) above average. As a result, the 12 months ending June 30, 2012, were the warmest 12-month period on record for the United States. This unusual heat wave, more intense than any on record, led to the declaration of the largest natural disaster in the history of the United States. Fifty-six percent of the continental United States was enveloped in intense drought conditions and the U.S. Department of Agriculture declared a nationwide state of emergency.

If we don’t act to lessen the cause of global warming and adapt our socioeconomic systems to the new reality that has emerged, we may leave our children—and all living things—with a world characterized by the most dangerous consequences of climate change.

1.5 Reliable Sources of Climate Change Information

“Global warming” refers to an increase in the average temperature of Earth’s surface, including the air, land, and oceans. Global warming is not a political position. It is a scientific certainty that has been verified by independent studies of literally thousands of scientists.

A 2009 study of scientific consensus on global warming published by the American Geophysical Union concludes:

The debate on the authenticity of global warming and the role played by human activity is largely nonexistent among those who understand the nuances and scientific basis of long-term climate processes. The challenge, rather, appears to be how to effectively communicate this fact to policy makers and to a public that continues to mistakenly perceive debate among scientists.

Multiple studies published in peer-reviewed scientific journals show that 97 percent or more of actively publishing climate scientists agree that: Climate-warming trends over the past century are very likely due to human activities. In addition, most of the leading scientific organizations worldwide have issued public statements endorsing this position.

The release of greenhouse gases is a result of burning fossil fuels (coal, natural gas, petroleum), industrial agriculture, and deforestation. This has led to their accumulation in the atmosphere in concentrations that have not been seen in millions of years of geologic history. These are heat-trapping gases, and consequently, the temperature of the atmosphere and the oceans has been rising for over a century at an accelerating pace.

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189 US Environmental Protection Agency: http://www3.epa.gov/climatechange/
1.5.1 Climate Data

Several groups collect data on global temperature. In the U.S., climate data are collected, maintained, and analyzed by the NASA Goddard Institute of Space Studies (GISS)\(^\text{191}\) and the National Oceanographic and Atmospheric Administration (NOAA).\(^\text{192, 193}\) Because climate knows no boundaries, both these organizations work closely with governments and researchers worldwide (Figure 1.9). In the United Kingdom, the Met Office Hadley Center (UKMET)\(^\text{194}\) is the foremost climate change research center, with responsibility to collect and analyze global climate information. The Japan Meteorological Agency\(^\text{195}\) provides weather observation and forecasting and climate change and global environmental tracking services. These units along with researchers at universities,\(^\text{196}\) government offices, and institutions around the world conduct scientific investigations and publish their results in peer-reviewed journals and reports.

1.5.2 Media

One would expect that mainstream media accounts of science would be generally reliable, but this is not always the case. Headlines are often conceived to sell controversy, not communicate fact. It is important to read past the headlines and filter personal opinion from scientific observation. Other sources of information include websites,\(^\text{197}\) institutional reports, and newsletters.\(^\text{198}\)

1.5.3 Scientific Peer Review

The peer-review process, while not perfect, is the best available system for assessing the accuracy of scientific findings and ensuring that a rigorous standard applies to the work of those who report on the results of their research. Typically, peer review begins when a scientist sends a manuscript describing the results of a research project to the editor of a scientific journal and requests publication. The editor reviews the work and, if it is deemed appropriate for the journal, sends it to specialists in the field to get their opinions on its quality. The specialists return their review within a few weeks and recommend publication, revision, or rejection. It is common for different reviewers to have conflicting opinions, and it is up to the editor to sort this out. On the basis of these comments, the editor makes a decision to publish the piece, reject it, or request revisions from the author subject to further review.

Peer-reviewed research forms the basis of improving our understanding of the details of climate change. What are the characteristics of changing air temperature? How rapidly is the ocean warming and how is this affecting

![Figure 1.9 Global annual average temperature anomalies (°C, relative to the long-term average for 1981–2010). Six datasets are shown as indicated in the legend. Gray shading, 95% uncertainty. The horizontal gray line with yellow shading indicates approximate point at which temperatures exceed 1°C above “preindustrial” levels. At the top, the horizontal line with the grey band is the difference from the 1850–1900 average. (bottom) differences of each data set from HadCRUT4 (the Met Office data set) on an expanded scale. Source: https://www.metoffice.gov.uk/research/news/2018/global-surface-temperatures-in-2017](https://www.metoffice.gov.uk/research/news/2018/global-surface-temperatures-in-2017)
marine ecosystems? Are there shifts in precipitation patterns, global winds, snow cover, and storminess? These and other questions drive the engine of climate research so that scientists are constantly building knowledge.

A study of 120 research articles published in the field of climate research between 1997 and 2013 found that climate researchers do not conceal uncomfortable facts that could potentially disprove climate change. Study authors concluded, “It was gratifying to see that the scientific method is robust. It is important to show that we can trust the results of climate research, even if more work is needed about how those results are reported.”

1.5.4 Climate Literacy

Established in 1989 under the Executive Office of the President, the U.S. Global Change Research Program (USGCRP) coordinates and integrates the climate change activities of 13 federal departments and agencies. The program is a ready source of peer-reviewed summaries on the subject of climate change and its impacts in the United States and the world.

The USGCRP has produced a short guide for educators to promote climate literacy among individuals and communities: The Climate Literacy Guide. This guide provides a summary of essential principles underlying how Earth’s climate system works and how climate change is occurring. The guide lists seven principles:

1. The Sun is the primary source of energy for Earth’s climate system.
2. Climate is regulated by complex interactions among components of the Earth system.
3. Life on Earth depends on, is shaped by, and affects climate.
4. Climate varies over space and time through both natural and human-made processes.
5. Understanding of the climate system is improved through observations, theoretical studies, and modeling.
6. Human activities are affecting the climate system.
7. Climate change will have consequences for the Earth system and human lives.

This and the following chapters expand on many of these principles.

1.5.5 IPCC Assessments

Because the public and their leaders and decision-makers may not keep up on the latest scientific research, it is important to provide summaries of improving climate knowledge to stakeholders on a regular basis. This is a key role of the Intergovernmental Panel on Climate Change (IPCC). The IPCC is an international organization under the joint auspices of the United Nations Environmental Program and the World Meteorological Organization. The IPCC produces global assessments of climate change every 5 to 7 years representing the status of professional understanding.

Past IPCC reports have been published in 1990, 1995, 2001, 2007, and 2013. The next report, Assessment Report 6 (AR6), is scheduled for release as a series of special studies. In 2018, a special study reported on the impacts of global warming of 1.5 degrees Celsius (2.7 degrees Fahrenheit) above preindustrial levels and related global greenhouse gas emission pathways.

The IPCC also has reports on: climate change and oceans and the cryosphere; climate change, desertification, land degradation, sustainable land management, and food security; and greenhouse gas fluxes in terrestrial ecosystems. These are part of the AR6 cycle. The main AR6 report, released in three working group contributions in 2020/2021 and a Synthesis Report in 2022, can be accessed at their website.

The IPCC does not carry out original research, nor does it do the work of monitoring climate or related phenomena. Its primary role is publishing special reports that assess the state of climate science on topics relevant to the implementation of the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC is an international treaty that acknowledges the possibility of harmful climate change. The IPCC is organized in three working groups. Working Group I reports on the physical science basis of climate change. Working Group II reports on climate change impacts, adaptation, and vulnerability. Working Group III reports on mitigation of climate change.

Knowledge about global warming can be acquired from IPCC assessment reports. For instance, Assessment Report 5 [AR5] was published in 2013 and 2014 and provides an advanced, detailed, and thorough review of global, regional, and local climate patterns and processes. The findings of AR5 are discussed in more detail in Chapter 6.

Knowledge can also be gained from peer-reviewed scientific literature published between IPCC assessments in reputable journals such as Science, Nature, Nature Climate

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202 IPCC: http://www.ipcc.ch/
204 All countries are members of this international treaty, the United Nations Framework Convention on Climate Change. The UNFCCC is designed to consider what can be done to reduce global warming and to cope with whatever temperature increases are inevitable. See their homepage: http://unfccc.int/2860.php
205 The 2013/2014 Fifth Assessment Report (AR5) consists of four elements, one from each of the three working groups and a Synthesis Report. All four reports, as well as past reports, can be found at: https://www.ipcc.ch/report/ar5/
206 Science: http://www.sciencemag.org/
207 Nature: http://www.nature.com/
Chapter 1 Evidence of Climate Change

1.5.6 Climate Change Impacts in the United States

The U.S. Global Change Research Program\textsuperscript{212} publishes congressionally mandated reports that summarize the state of knowledge regarding climate impacts globally and across the United States. The National Climate Assessment is conducted every 4 years to assess and inform the Nation about the impacts of climate change. Teams of researchers from across the United States author the report. It is a very inclusive and collaborative process and provides a comprehensive assessment of national climate impacts.

In late 2017, the Fourth National Climate Assessment, NCA4, published a Climate Science Special Report\textsuperscript{213} that provided reviews of the state of scientific understanding of a range of topics including sea-level rise, extreme weather, projections of climate change, ecosystem impacts, and others.

Key findings\textsuperscript{214} from the NCA4 Executive Summary\textsuperscript{215} are as follows:

1. The global, long-term, and unambiguous warming trend has continued during recent years. Since the last National Climate Assessment was published, 2014 became the warmest year on record globally; 2015 surpassed 2014 by a wide margin; and 2016 surpassed 2015. Sixteen of the warmest years on record for the globe occurred in the last 17 years (1998 was the exception).

2. Annual average temperature over the contiguous United States has increased by 1.8°F (1.0°C) for the period 1901–2016 and is projected to continue to rise (very high confidence).

3. There have been marked changes in temperature extremes across the contiguous United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records (very high confidence).

4. Heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901 (high confidence). There are important regional differences in trends, with the largest increases occurring in the northeastern United States (high confidence).

5. Extreme temperatures in the contiguous United States are projected to increase even more than average temperatures (very high confidence).

6. Future decreases in surface soil moisture from human activities over most of the United States are likely as the climate warms under the higher scenarios (medium confidence).

7. The world’s oceans have absorbed about 93% of the excess heat caused by greenhouse gas warming since the mid-20th century, making them warmer and altering global and regional climate feedbacks (very high confidence).

8. Global mean sea level has risen by about 7–8 inches (about 16–21 cm) since 1900, with about 3 in (about 7 cm) occurring since 1993 (very high confidence) (Figure 1.10).

9. The world’s oceans are currently absorbing more than a quarter of the CO₂ emitted to the atmosphere annually from human activities, making them more acidic (very high confidence), with potential detrimental impacts to marine ecosystems.

\textsuperscript{208} Nature Climate Change\url{http://www.nature.com/nclimate/index.html}

\textsuperscript{209} Science Daily\url{https://www.sciencedaily.com/news/earth_climate/}

\textsuperscript{210} Daily Climate\url{http://www.dailyclimate.org}

\textsuperscript{211} Google Alerts\url{https://www.google.com/alerts}

\textsuperscript{212} USGCRP: \url{http://www.globalchange.gov/}


\textsuperscript{214} Findings in NCA4 are evaluated through two metrics: Confidence in the validity of a finding based on the type, amount, quality, strength, and consistency of evidence (such as mechanistic understanding, theory, data, models, and expert judgment); the skill, range, and consistency of model projections; and the degree of agreement within the body of literature. Likelihood, or probability of an effect or impact occurring, is based on measures of uncertainty expressed probabilistically (based on the degree of understanding or knowledge, e.g., resulting from evaluating statistical analyses of observations or model results or on expert judgment).

\textsuperscript{215} USGCRP (2017)

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure110.png}
\caption{Figure 1.10 As sea level rises, it erodes previously stable shorelines and accelerates erosion on shores that were already eroding. Source: Dolan Eversole, University of Hawaii Sea Grant.}
\end{figure}
10. Annual average near-surface air temperatures across Alaska and the Arctic have increased over the last 50 years at a rate more than twice as fast as the global average temperature (very high confidence).

11. Since the early 1980s, annual average Arctic sea ice has decreased in extent between 3.5% to 4.1% per decade, has become thinner by between 4.3 and 7.5 ft, and is melting at least 15 more days each year. September sea ice extent has decreased between 10.7% and 15.9% per decade (very high confidence).

12. The observed increase in global carbon emissions over the past 15–20 years has been consistent with higher scenarios. In 2014 and 2015, emission growth rates slowed as economic growth became less carbon-intensive. Even if this slowing trend continues, however, it is not yet at a rate that would limit the increase in the global average temperature to well below 3.6°F (2°C) above preindustrial levels.

13. Choices made today will determine the magnitude of climate change risks beyond the next few decades.

14. Unanticipated and difficult or impossible-to-manage changes in the climate system are possible throughout the next century as critical thresholds are crossed and/or multiple climate-related extreme events occur simultaneously.

1.5.7 United Nations Framework Convention on Climate Change

In 1992, at an international conference in Rio de Janeiro, an environmental treaty was negotiated among the world’s nations and entered into force in 1994. Known as the United Nations Framework Convention on Climate Change (UNFCCC), the treaty objective was to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous human interference with the climate system. The UNFCCC has been signed by 198 parties (nations for the most part) and is broadly viewed as a lawful and legitimate agreement due to its global membership. Since 1995, there have been annual meetings, called Conference of the Parties (COPs), wherein member nations assess progress in dealing with climate change.

In 1997, under the auspices of the UNFCCC, representatives of the United States and 83 other nations met in Kyoto, Japan, to establish legally binding obligations for developed countries to reduce their greenhouse gas emissions. The result of their deliberations was the Kyoto Protocol, an international agreement that carbon dioxide emissions should be regulated. The protocol proposed establishing carbon quotas for each country based on its population and level of industrialization. A carbon quota is a fixed permissible amount of CO₂ that a country is allowed to release to the atmosphere each year.

For example, the Kyoto Protocol required that by 2012, industrialized countries such as the United States reduce their carbon dioxide emissions to 7 percent below the levels measured in 1990 and by 20 percent by 2020. As the leading developed nation, the United States has historically produced the bulk of the world’s carbon dioxide emissions. Then, in 2007, China’s output surpassed that of the United States. Today, powerful economic growth in India is rapidly escalating emission production there as well.

The United States never signed the Kyoto Protocol because the U.S. Congress refused to endorse the treaty, yet it reached the 2012 goal nonetheless, due in part to an economic recession that began in 2008, improved automobile fuel efficiency, and growth in the use of natural gas as an energy source, which results in less carbon release to the atmosphere than burning traditional coal or oil.

The COP21, which met in Paris in late 2015, produced a landmark covenant replacing the Kyoto Protocol. Known as the Paris Agreement, it lays out global commitments on climate change reduction measures from 2020. The agreement entered into force with the joining of at least 55 countries that together represent at least 55 percent of global greenhouse gas emissions. On April 22, 2016 (Earth Day), 174 countries signed the agreement in New York and began the work of adopting it within their own legal systems (called “ratification”). The expected primary result of the agreement is to limit global warming to less than 2 degrees Celsius (3.6 degrees Fahrenheit), compared to preindustrial levels, and to reach zero net anthropogenic greenhouse gas emissions during the second half of the 21st century.

The Paris Agreement also contains language to pursue efforts to limit the temperature increase to 1.5 degrees Celsius (2.7 degrees Fahrenheit), which will require reaching zero emissions sometime between 2030 and 2050. The future of the UNFCCC, and the Paris Agreement, is to establish protocols for monitoring individual nations’ emissions. Because it has been calculated that the reductions agreed to by member nations thus far are not sufficient to limit warming to 2 degrees Celsius, the UNFCCC also works to establish new agreements that continue the process of lowering future greenhouse gas emissions.

For more on the Paris Agreement, see the box Spotlight on Climate Change, “COP 21.”

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216 UNFCCC: http://unfccc.int/2860.php
217 UNFCCC: http://unfccc.int/kyoto_protocol/items/2830.php
218 During periods of recession in the U.S. and elsewhere, greenhouse gas emissions tend to decrease because manufacturing and other industrial activities decrease.
219 UNFCCC: http://unfccc.int/paris_agreement/items/9485.php
Chapter 1  Evidence of Climate Change

COP21
In late 2015, under the guidance of the United Nations, 195 nations pledged to stop global warming temperatures “well below” 2°C (3.6°F) and if possible, below 1.5°C (2.7°F). This landmark climate treaty was signed in Paris (Figure 1.11) at the Conference of Parties 21, or COP21, the 21st year of meetings designed to achieve such an agreement.

Hailed as a “turning point,” a “victory for the planet,” and “the end of the era of fossil fuels,” the agreement is a major milestone in over two decades of effort to get the world to unify under a single plan to halt global warming.

But in truth, the decreased greenhouse gas emissions approved in Paris will fail to halt warming at the agreed target. Global temperatures will sail past 2°C and not likely stop until passing 3°C (5.4°F) in the second half of this century. In fact, a global study of gross domestic product (GDP) per capita and carbon intensity, concluded that the likely range of warming by the end of the century is 2.0 to 4.9°C (3.6 to 8.8°F) with a median temperature of 3.2°C (5.7°F) above the natural background. They calculate there is only a 5% chance that warming will be less than 2°C, and a 1% chance of it being less than 1.5°C.

Emissions that have already been discharged through 2015 have locked in 1.3 to 1.7 m (4.3 to 5.6 ft) of global sea-level rise when the temperatures of the ocean, the air, and the melting ice all reach equilibrium. Deep cuts in greenhouse gas emissions of 40 to 70% by mid-century will be needed to avert the worst of global warming. These cuts will require a tripling or a quadrupling of the share of low-carbon energies including solar, wind, or nuclear power.

In light of these hard truths, how should we interpret the victory in Paris? A giant shove in the right direction might be an apt assessment. Binding nearly 200 countries to a global framework is no small feat, but the world needs to continue to “up its game.” Here are some critical steps that the global human community must take if COP21 is to achieve its goals.

1. Every nation must ratify its commitment. That is, the committed decrease in greenhouse gas emissions must take on legal status within each nation. At this writing, 175 of the 197 parties to the convention have ratified the agreement in their own nations.

2. Governments of the world need to end the practice of subsidizing the production of fossil fuels. These subsidies often take the form of tax relief for oil and coal companies and outright investments by nations in producing fossil fuels. Experts have estimated that over $600 billion in subsidies is provided every year to offset expenses in producing carbon fuels.

Box 1.2  Spotlight on Climate Change

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223 Raftery et al. (2017)
225 Reuters: http://www.reuters.com/article/us-climatechange-solutions-idUSKBN0G71SF20140807
1.6 How Unusual is the Present Warming?

To identify the difference between the present warming and natural climate changes, it is useful to study climate in a longer geologic context. A number of studies have done this.

One approach is to search the geologic record of the past several thousand years for simultaneous changes in the Northern and Southern Hemispheres (“global” warming) such as happened over the past century. Svante Björck, a climate researcher at Lund University in Sweden, used this approach and showed that simultaneous warming of the two hemispheres has not occurred in the past 20,000 years. This is as far back as it is possible to analyze with sufficient precision to compare with modern climate changes occurring at a rapid pace. His study concludes that what is happening today is unique from a historical geological perspective.

1.6.1 Unprecedented Warming

Several independent studies confirm that recent warming is unprecedented in both magnitude (the amount of warming) and speed (the rate of warming). A study of North Atlantic currents flowing into the Arctic highlights the fact that the Arctic is responding more rapidly to global warming than most other areas on our planet. Researchers concluded that early 21st century temperatures of Atlantic water entering the Arctic Ocean are unprecedented over the past 2,000 years and are presumably linked to the Arctic amplification of global warming.

These facts have raised alarms among scientists, some of whom have concluded that the Arctic Ocean is already suffering the effects of a dangerous climate change. Another study concluded that 20th century warming of deep North Atlantic currents has had no equivalent during the last 1,000 years. Still another research effort concluded that the past few decades have been characterized by a global temperature rise that is unprecedented in the context of the last 1,600 years.

Research by the National Center for Atmospheric Research concluded that Arctic temperatures in the 1990s and 2000s reached their warmest level of any decade of the past 2,000 years. They found that the Arctic would be experiencing a long-term cooling trend (due to the nature of Earth’s orbital configuration with the Sun) were it not for greenhouse gases that are overpowering natural climate patterns.

The aggregate conclusion of these independent studies is unmistakable. Present warming is unprecedented in recent geologic history, no natural mechanism can be identified accounting for modern climate change, and human greenhouse gas emissions have the obvious potential to be the cause of the present warming.

In 2006, the U.S. Congress asked the National Research Council (NRC) to study Earth’s climate and report on the levels of warming in recent history. The NRC concluded that Earth’s average surface temperature today is the highest of the past 1,300 years. Their report states that Earth’s surface warmed 0.6 degrees Celsius (1 degree Fahrenheit) during the 20th century and is projected to warm by an additional (approximately) 2–6 degrees Celsius (3.6 to 10.8 degrees Fahrenheit) during the 21st century. Global average temperature measurements by instruments indicate a near-level trend from 1856 to about 1910, a rise till 1945, a slight decline to about 1975, and a rise to the present. Global warming is also verified by several independent sources including the National Climatic Data Center, NASA, U.K. Met Office, Japan Meteorological Agency, and others.

3. Put a global tax on carbon pollution. By taxing carbon, we would be charging those who use carbon fuels for the damage they do to the environment and the threats to public health and safety, a justifiable cost that will decrease the use of fossil fuels and increase the production of clean energies.

4. Invest in greener technologies that can take the place of dirty carbon energy.

5. Step up global commitments to decreasing greenhouse gas production.
1.7 Surface Temperature

How, when, and why heat is distributed across the planet surface, is critical to the existence of life in every region and environment on Earth. The total amount of heat, and its variation from place to place, drive global winds that circulate the atmosphere and control regional weather patterns, rainfall, growing seasons, and living conditions to which humans have adapted since civilization began.

Earth is the right distance from the Sun (about 148 million km; 92 million mi), has the right combination of gases in its atmosphere, and has water covering more than 70 percent of the planet’s surface, which allow the origin and evolution of life and the resources necessary to sustain life. As far as we know, no other planet in our solar system has the thermal, physical, and chemical conditions that allow life to exist. This is what makes our blue planet unique and habitable.

However, global warming threatens severe changes to aspects of this system, including the temperature regime under which human civilization has developed, the location and distribution of agriculture and other protein sources that sustain us, the natural ecosystems that provide important services, and the supply of water around which we have built communities. By studying climate change, we gain critical knowledge that will support efforts to adapt to, and mitigate the negative impacts of, global warming (Figure 1.12).

FIGURE 1.12 Observations of global climate change. (A.) Average annual Earth’s surface temperature relative to the average over the period 1986–2005. (B.) Annual average global sea level. (C.) Atmospheric concentrations of the greenhouse gases carbon dioxide (CO₂, upper line) methane (CH₄, middle line) and nitrous oxide (N₂O, lower line) determined from ice core data (prior to the 1960s) and from direct atmospheric measurements. (D.) Global anthropogenic carbon emissions per year from burning of fossil fuel including gas and cement production. Cumulative annual emissions of carbon from these sources (upper line).²³⁷

Source: N. Hulbirt

²³⁷ Figure after Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure TS.6. Cambridge University Press.
1.7.1 Sensors

Several types of independent sensors have documented warming over the past decade. Weather balloon measurements have found that the global mean near-surface air temperature is warming by approximately 0.18 degrees Celsius (0.32 degrees Fahrenheit) per decade, satellite measurements of the lower atmosphere show warming of 0.16 to 0.24 degrees Celsius (0.29 to 0.43 degrees Fahrenheit) per decade since 1982, continental weather stations document warming of approximately 0.2 degrees Celsius (0.36 degrees Fahrenheit) per decade, and ocean measurements using various types of sensors show persistent warming since 1970.

The ocean has been a great ally to land dwelling ecosystems, absorbing over 90 percent of the excess heat trapped by greenhouse gases. However, the ocean’s ability to store this heat is not limitless, and it has paid a price. Warming of the ocean is causing marine species to move to new, cooler locations, and natural relationships involving mating, predator–prey, interspecies contact, and seasonal migration are being affected. The oceans are now taking up heat at twice the rate they were only two decades ago.

Notably, consistent with theory, satellite records of warming in the layers of the atmosphere near Earth’s surface are matched by simultaneous cooling in the higher layers of the atmosphere (Figure 1.13). This makes perfect sense given that greenhouse gases trap heat at Earth’s surface and therefore limit heat flow into overlying layers.

1.7.2 Excess Heat

In a normal planetary atmosphere where the amount of heat arriving from the Sun equals the amount that radiates back out to space, the temperature would not change and global warming would not occur. We discuss this concept in Chapter 2. Temperature would be stable within a certain band of variability. However, with increasing greenhouse gases, the amount of heat radiating back out to space is less than the amount arriving from the Sun, and the difference is trapped near Earth’s surface by carbon dioxide and other anthropogenic gases.

By dissecting the temperature record of the past 160 years, researchers have been able to define the components of temperature change that are the result of volcanic eruptions, the El Niño Southern Oscillation, variations in the Sun’s energy, and warming due to increasing greenhouse gases. Finding that more than 90 percent of the excess heat trapped by greenhouse gases has been absorbed by the oceans, the study concludes that since 1850 and 1950, approximately 75 and 100 percent, respectively, of the observed global warming is due to human influence.

In fact, it was determined that greenhouse gas emissions are responsible for 166 percent of the observed warming since 1950; that is, there would have been more greenhouse warming produced over the period, but it has been offset by aerosols (fine particles that reflect sunlight in the upper atmosphere, thus providing a cooling effect) produced by human manufacturing.

1.8 Human Fingerprints on Climate

The world is changing in significant ways that are most simply explained in the context of global warming. Taken together, the thousands of observations of changing ecosystems, environments, and natural processes that appear to be shifting in unusual fashion constitute a massive database pointing to the impacts of a warming world. But what is the evidence that humans are the cause? Several principal observations define a “human fingerprint” on climate change that the majority of the scientific community find sufficient to support the hypothesis Global warming is the result of industrial emissions of greenhouse gas.
FIGURE 1.13 Map of temperature trends 1979–2016 (degrees Celsius/decade) and 12 months running mean global temperature time series with respect to 1979–2016, in the lower troposphere (near surface) where temperature has risen in recent decades, and in the lower stratosphere (above the troposphere) where temperature has fallen because of heat trapping in the troposphere.\textsuperscript{244}


**Fingerprint #1: There is more industrial carbon in the atmosphere**

One clear human fingerprint is found in the type of carbon (C) released into the air by industrial emissions. Carbon, and other elements, occurs naturally in forms known as isotopes. In the case of carbon, there are three forms: $^{12}$C, $^{13}$C, and $^{14}$C. While engaging in photosynthesis, plants prefer to absorb CO$_2$ wherein the carbon is composed of the lighter form, $^{12}$C. Petroleum is composed largely of fossilized marine algae, and coal is composed of fossilized terrestrial wetland plants; thus, both energy sources contain high abundances of light carbon ($^{12}$C) because they come from fossil plants. This can be measured using the ratio of the two types of carbon: $^{12}$C/$^{13}$C.

In plants, $^{13}$C/$^{12}$C is relatively low (i.e., the amount of $^{12}$C is high). Burning oil and coal releases this light carbon, which immediately combines with oxygen in the atmosphere to form $^{12}$CO$_2$; thus, we should be able to detect a decrease in $^{13}$C/$^{12}$C in the atmosphere as more fossil fuel emissions accumulate.

Indeed, this is exactly what is found. Measurements of the ratio of $^{13}$C/$^{12}$C in the air, and in corals, and in sponges that take up atmospheric carbon (mixed with seawater) reveal a strong decrease in $^{13}$C/$^{12}$C over the past 200 years, with a significant acceleration in the decrease since about 1960–1970. Thus, the growth of carbon dioxide in the atmosphere is wholly attributable to combustion of coal and petroleum; humans are raising the CO$_2$ level.

Another aspect of burning carbon is that when unburned carbon enters the air, it uses two oxygen atoms to form the molecule CO$_2$—it thus draws down the level of oxygen in the atmosphere. Measurements of oxygen not only show this decline, but the rate of decline is consistent with the rate of CO$_2$ increase.

**Fingerprint #2: Less heat is escaping to space**

Direct evidence that more carbon dioxide causes warming is found in the fact that less heat is escaping into space. As discussed earlier, carbon dioxide traps IR radiation (proven by modern laboratory experiments and as early as 1859 in laboratory measurements by John Tyndall from the planet surface that would otherwise escape to space. A decrease in the IR energy emitted by Earth from 1979 to 2016 has been detected by satellites and has since been verified by additional measurements. Because this heat is trapped in the lowest atmospheric layer, the troposphere, it is warming the air and Earth’s surface.

**Fingerprint #3: Oceans are warming from the top down**

The oceans are warming in the only manner possible under an enhanced greenhouse: from the top down. Measurements of ocean warming show that the water temperature has a depth profile that varies widely by ocean; natural internal climate variability, increased heat from Earth’s mantle, or solar and volcanic forcing cannot explain it. The pattern of warming is complex, but it has been captured by sensors that depict the upper layer of the oceans (varying from 75 to 500 m [246 to 1,640 ft] depth) warming in a way that is consistent with models simulating human production of greenhouse gases.

**Fingerprint #4: Nights are warming faster than days**

During the day, sunlight heats the air. At night, the air cools by radiating heat out to space. Greenhouse gases trap part of this heat. Thus, in a situation where the Sun has not increased its output, but the greenhouse effect is increasing, nights will become warmer faster than days. That is, if global warming were caused by the Sun, we would expect to see that the days would warm faster than the nights. Observations clearly show that nights are warming faster than days. Thus, the detailed pattern of global warming is consistent with an amplified greenhouse effect (resulting from growing emissions of heat-trapping gases).

**Fingerprint #5: More heat is returning to Earth**

Radiation works both ways. IR radiation can be measured moving upward from a warm Earth surface as well as moving (Continued)
downward from a warm atmosphere. With an enhanced greenhouse effect, where the molecules of CO$_2$, CH$_4$, CFCs, and other greenhouse gases are reradiating heat (IR) in all directions, one would expect to observe an increase in downward IR radiation from the troposphere to the ground. As expected, this has been directly observed.$^{259}$ In fact, researchers state, “This experimental data should effectively end the argument by skeptics that no experimental evidence exists for the connection between greenhouse gas increases in the atmosphere and global warming.” Thus, because of an amplified greenhouse effect due to industrial emissions, more heat is returning to Earth.

**Fingerprint #6: Winter is warming faster than summer**

If the Sun were causing global warming, you would continue to see a seasonal effect in the warming pattern. But that is not what we see. Data show that winter is warming faster than summer. That is, temperature is becoming more uniform throughout the year. One way to think about this is to realize that in an atmosphere that is uniformly warming under an amplified greenhouse effect, a cool winter would be more out of equilibrium with the rising temperature than summer. Thus, one would expect winter to warm faster than summer. This is exactly what has been observed.$^{260}$

**Fingerprint #7: The stratosphere is cooling**

A corollary to fingerprint #2 (less heat is escaping to space) is that less heat is finding its way to the stratosphere. Because the amplified greenhouse effect is located in the troposphere near Earth’s surface, industrial greenhouse gases below are trapping heat that would otherwise find its way to the atmospheric layers above. As a result, satellites and weather balloons are recording$^{261}$ cooling temperatures in the stratosphere simultaneous with warming in the troposphere (see Figure 1.13).

**Fingerprint #8: Physical models require human greenhouse gas emissions**

As we will see in Chapter 6, the fundamental laws of nature that explain the movement of heat, the behavior of molecules, and the physics of natural processes, can be programmed to build computer models of climate. These are basically larger and more complex versions of computer models that are used to predict the weather on the TV news every day. When these models attempt$^{262}$ to simulate the past century of warming using only natural factors (e.g., variations in sunlight, volcanic eruptions, and other natural climate processes), they instead predict global cooling. But when human emissions of greenhouse gases are introduced to the models along with the natural factors, they faithfully reproduce the observed temperature record: global warming. In fact, researchers$^{263}$ have found that computer models are growing in sophistication and accuracy to the point that they are approaching direct observation of the planet as a reliable source of information.

**Fingerprint #9: Multiple and independent lines of evidence**

Attributing global warming to industrial emissions is not only the consensus among the scientific community, it is the common explanation for multiple and independent lines of evidence. Direct observations show the following.

1. There is more industrial carbon in the atmosphere, and it is amplifying the greenhouse effect.
2. Less heat is escaping to space.
3. Oceans are warming from the top down.
4. Nights are warming faster than days.
5. More heat is returning to Earth’s surface from the atmosphere.
6. Winter is warming faster than summer.
7. The stratosphere is cooling.
8. Physical laws of nature predict global warming consistent with observations.

Most of the scientific community finds the authenticity and agreement of these observations amply sufficient to support the hypothesis that Global warming is the result of industrial emissions of greenhouse gases and other human activities.


A Consistent Picture Emerges

In a warmer world caused by greenhouse gas emissions, one would expect to observe certain changes including melting glaciers, warming and acidifying oceans, sea-level rise, changes in ecosystems, plant and animal extinctions, new patterns in the weather, and long-term changes in temperature (Figure 1.14a) and precipitation (Figure 1.14b). In fact, these have all been observed.

For example, Greenland ice and Antarctic ice are melting at an accelerating rate. Sensors on satellites have measured this over a sufficient period (nearly two decades) that we not only know melting is a persistent annual trend but also know that the rate of melting is accelerating from one year to the next. In fact, the melting has become so persistent that researchers now conclude that the melting of the West Antarctic Ice Sheet has become irreversible.

The ocean is getting warmer and it is acidifying as it mixes with an atmosphere that is enriched with excess carbon dioxide. The concentration of dissolved CO$_2$ in the ocean grows with each year. Not surprisingly, both warming and acidification are occurring at rates that are predicted by long-established chemical and physical theory.

Sea level is rising, and the rate of rise has accelerated. This is an anticipated consequence of a warming world.

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267 Rignot et al. (2014)


269 Nerem et al. (2018)

270 Dangendorf et al. (2017)
In a warming world, it would be expected that the southern line of permanently frozen ground (permafrost) would begin to migrate to the north as warmer climate zones expand in the northern hemisphere. Indeed, this has already been observed in Canada. Simultaneously, the boundaries of the tropics, defined by temperature, rainfall, wind, and ozone patterns, have shifted poleward by at least 2° latitude in the past 25 years.

Excess heating of the tropics has sped up the rate of evaporation and atmospheric circulation so that surface winds have accelerated nearly around the entire planet. These and many other phenomena stand in testimony to the reality of warming and, taken as a whole, are consistently in keeping with expectations of how a warmer atmosphere would change the world.

Global warming is also changing the weather. In the past decade, the United States experienced twice as many record daily high temperatures than record lows; that is, the hotter days are getting hotter and the colder days are getting hotter. Throughout the spring, summer, and fall of every record-setting hot year, thousands of daily high temperature records are set across the United States, outnumbering the daily record lows by as much as 116 to 1 (February, 2017), which exceeds the 2 to 1 average of the previous decade.

In the summer of 2012, the United States experienced a prolonged heat wave that severely impacted agricultural production that year. In fact, extreme weather events are expected to grow in frequency and magnitude as the world continues to warm. Ecosystem changes are occurring as well. Mild winters in British Columbia allow an infestation of the boring mountain pine beetle and warming oceans have led to coral bleaching, a problem in some hot months that has reached epidemic proportions. There are many other examples of observed changes around the world that are consistent with expected impacts of warming, and these are highlighted throughout this textbook.

1.9.1 Optimism about Climate Change?

There is hope that the mounting evidence of climate change, and that humans are the cause, may be having an impact on community attitudes across the globe. The annual rate of global carbon dioxide emissions slowed in 2014, 2015, and 2016. But in 2017 it surged upwards by 1.5 percent on increased emissions from developing nations (Figure 1.15).

In the decade of the 2000s, global carbon dioxide emissions grew at an average annual rate of 3.5 percent greater than the previous year. Over the decade 2006–2015, the rate of increase slowed to 1.8 percent and slowed further

![Figure 1.15](https://example.com/figure1.15.png)
to essentially zero growth over the period 2014–2016. Remarkably, this stabilization in the rate of carbon dioxide growth occurred at the same time that the world economy grew at more than 3 percent per year—decoupling greenhouse gas emissions from economic growth for the first time.  

Slowing, and eventually stopping, the production of greenhouse gases from industrial activities requires the directed energies of all the world’s economies. The recent slowdown in global missions suggests that efforts to move away from coal and oil, toward renewable energy, are beginning to have an effect (despite the uptick in 2017). To achieve falling greenhouse gas emissions, global businesses, nations, families, and individuals must be attentive to their carbon footprint; a measure of how much one’s daily activities are responsible for raising greenhouse gases.

A number of short-lived greenhouse gases with atmospheric lifetimes of under a few decades contribute significantly to the radiative forcing that drives climate change. Some experts argue that aggressively reducing the release of these “short-lived gases” should be an essential part of any climate mitigation strategy. The prime targets for this mitigation include methane, hydrofluorocarbons, black carbon, and ozone. However, one report argues that the benefits of early short-lived gas mitigation have been greatly exaggerated. The reason is that CO$_2$, because of its long atmospheric residence time, causes nearly irreversible climate change persisting millennia after emissions cease.

For instance, for a sudden pulse of carbon dioxide in the atmosphere that raises the concentration to 1,250 parts per million over preindustrial levels (which were about 280 parts per million), about 900 parts per million of carbon dioxide will still be up there after 100 years. Indeed, concentrations will only decline to 675 parts per million over another 900 years.

Eventual mitigation of short-lived gases can make a useful contribution to halting global warming before it reaches catastrophic levels, but there is little to be gained by expending time and money on short-lived gases before stringent carbon dioxide controls are in place and have caused annual emissions to approach zero. Any earlier implementation of short-lived gas mitigation that replaces efforts to reduce CO$_2$ emissions will lead to a climate irreversibly warmer than would a strategy with an all-out focus on carbon dioxide. Short-lived gas mitigation does not buy time for implementing stringent controls on CO$_2$ emissions.

Thus, much of the carbon pollution emitted over the last few centuries is very much still with us. It’s still determining our future even today, which means that the global warming that the world is currently experiencing will continue and accelerate as long as we persist in using fossil fuels. . . . and well beyond that.

See the box “Spotlight on Climate Change,” “Community Resilience.”

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**Box 1.3 | Spotlight on Climate Change**

**Community Sustainability and Resilience**

Over the past five decades, the average temperature of the atmosphere has increased at the fastest rate in recorded history. Under this trend, the average temperature could be 4.0 to 6.0°C (7.2 to 10.8°F) higher by the end of the century. In those conditions, cities will be exposed to heat waves, extreme weather, crippling summer temperatures, water shortages, drought, high-energy demand for air-conditioning, and food shortages.

Global warming is making life more dangerous. To adjust to this new reality, cities, towns, and suburbs can take steps to increase their sustainability and resilience in the face of climate change (Figure 1.16). Sustainable and resilient communities are characterized by:

- **Local food production**—Local and regional food production helps to eliminate dependence on greenhouse gas intensive global industrial food systems.
- **Green LEED**—LEED-certified buildings use less water and energy and produce less greenhouse gas emissions. Companies that specialize in LEED building and other sustainability initiatives can ensure energy efficiency and healthier buildings.
- **Renewable energy production**—Replacing electricity generated by fossil fuels with renewable energy.

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energy made by solar, wind, hydro, geothermal, and other sources of clean energy help curb greenhouse gas emissions.

**Public transportation**—Reducing the use of single-occupant vehicles as people make their daily commutes means less carbon emissions.

**City design for ride/walkability**—Cities that are designed to promote walking and bicycling not only produce less emissions but also encourage healthy living.

**EV charging stations**—Cities wanting to see more electric vehicles replacing traditional gasoline-powered cars need to develop the infrastructure to support those changes.

**Water conservation**—Water conservation helps residents save money, prevents water pollution in local lakes, rivers, and watersheds, and helps ensure availability of water for future generations.

**Waste reduction**—Prevention and reduction efforts help to prevent waste from ending up in the landfill where it contributes to climate change, leads to pollution, and uses natural resources and energy to manage.

**City policies that encourage sustainability**—(ban plastic grocery bags, provide space for community gardens, etc.). From purchasing procedures, to city planning and permitting, to energy efficiency and recycling programs, city policies can significantly impact the way local governments and their residents act when it comes to environmental issues.

**Bring more vegetation into neighborhoods**—Green roofs, roadside plantings, vegetated swales, rain gardens, and other features improve storm water management, lower the temperature, and absorb carbon dioxide from the air.

**Plant community gardens**—Community gardens such as urban orchards and vegetable patches help lower temperature, and growing food in neighborhoods reduces the number of driving errands in a community.

**Drought-resistant landscaping**—Landscaping that does not require frequent watering is a way to save water, because water shortages are likely to become more frequent with warmer temperatures.

**Light-colored pavement, roofing, and other surfaces**—Dark colors absorb heat, but light surfaces reflect sunlight and lower the planet’s temperature. For instance, on the hottest day of the New York City summer in 2011, a white roof was found to be 23°C (42°F) cooler than a traditional black roof. This lowers electricity demand for air-conditioning, which in turn reduces carbon emissions from power plants.

**Stop building on coastlines**—Sea-level rise is real. It is already accelerating and storms, tsunamis, high waves, and high winds cause more damage.

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292 “City Gardens that Respect the Urban Fabric,” http://switchboard.nrdc.org/blogs/kbenfield/city_gardens_that_respect_the.html

when the ocean is higher. What used to be the storm of the century has now become the storm of the decade. Communities can adapt to sea-level rise, but planning needs to begin in advance of the problem.

**Save older buildings**—New construction generates heat, requires large volumes of water, disrupts vegetation, and adds to the carbon dioxide in the atmosphere.

**Follow new "Original Green Building Practices"**—Especially in a warmer climate, it is important that buildings be constructed and sited to make best use of natural advantages. These practices include building front porches and planting deciduous trees on the south side where they provide shade in summer and allow sun in the winter. Plant evergreens on the side that will benefit by protection from winter winds.

Use close-to-the-source materials and a naturally insulating design. Place new buildings in walkable settings with everyday conveniences nearby.

**Keep the community footprint small and well connected**—One characteristic of urban sprawl is that it is vehicle dependent, and transportation is a major source of carbon dioxide. Walkable and bikeable destinations, effective mass transit, and small-scale commuting and errands promote a low carbon footprint among communities.

**Update zoning and building codes**—Updated codes promote resilience and a low carbon footprint.

As you read through the following chapters, keep in mind the steps that you can take to lower your contribution to global warming and to increase your own safety in a warming world.

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### Animations and Videos

2. Global Warming: What we knew in 82. [https://www.youtube.com/watch?v=OmpiuuBy-4s](https://www.youtube.com/watch?v=OmpiuuBy-4s)
4. James Hansen in 2016 discussing growing concerns with global ice sheets. [https://www.youtube.com/watch?v=Ykn8_ayFqNL&t=25s](https://www.youtube.com/watch?v=Ykn8_ayFqNL&t=25s)
6. The Ocean, A Driving Force for Weather and Heat. [https://www.youtube.com/watch?v=6gvYTeuoDWY](https://www.youtube.com/watch?v=6gvYTeuoDWY)
7. Plate Tectonics. [https://www.youtube.com/watch?v=Xzpk9110Iyw](https://www.youtube.com/watch?v=Xzpk9110Iyw)
10. The Case for Optimism on Climate Change. [https://www.ted.com/talks/al_gore_the_case_for_optimism_on_climate_change](https://www.ted.com/talks/al_gore_the_case_for_optimism_on_climate_change)
11. Future Earth Global Carbon Budget. [https://www.youtube.com/watch?v=KWKFxhsAT94](https://www.youtube.com/watch?v=KWKFxhsAT94)

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### Comprehension Questions

1. What is the relationship between global warming and climate change?
2. Describe some of the scientific evidence that increased surface temperature is having measurable impacts on human communities and natural ecosystems.
3. Describe the principle features of the graph showing global temperature anomalies (Figure 1.5).
4. What evidence supports the conclusion that humans are the primary cause of global warming?
5. Describe the primary human activities causing the problem of global warming and climate change.
6. If global warming is real, why is the stratosphere cooling?
7. Temperature records show that climate varies strongly from one year to the next. What does this mean in terms of interpreting the data for the presence or absence of global warming?
8. What is the IPCC?
9. What can we expect the Earth to be like in the future if the climate crisis is not addressed?

Thinking Critically

1. Which aspect of climate change worries you the most? Why?
2. Suppose that a scientist reported that the climate has been cooling for several decades in one county in the central United States. What questions would you ask before accepting this information? And once you accept these data as true, what impact would they have on your understanding of global warming?
3. As mayor of a small town in Florida, what steps are you considering with regard to the problem of climate change?
4. Solar output over the period 2008–2010 was low, and scientists are predicting that this trend will continue for another decade or so before Sun’s heat recovers to normal levels. Describe the impact that low solar output could have on global warming both over the next decade and after.

5. As a homeowner planning on staying in your new home for at least 30 years, what proactive steps will you consider to adapt your house to climate change?
6. As a homeowner planning on staying in your new home for at least 30 years, what proactive steps will you consider to adapt your house to climate change?
7. What effects could heat waves have on a large city?
8. What is the average rate of global warming?
9. Describe a study designed to test the theory that humans are causing global warming.
10. Why is the weather very likely to change as climate changes?

Activities

1. Explore the following websites. What evidence is provided by each of these that climate is changing and humans are the most important cause?
   (a) NOAA Centers for Environmental Information: https://www.ncdc.noaa.gov
   (b) NASA Vital Signs: https://climate.nasa.gov
   (c) U.S. Global Change Research Program: http://www.globalchange.gov
2. NASA uses satellites to gather information about the increase in Earth’s temperature. Which climate aspects that satellites use for this purpose are mentioned in the NASA video “The Temperature Puzzle,” https://www.youtube.com/watch?v=DjILZWW6Ko0?
   (a) List the main points and explain why these are reasons to be optimistic about the climate problem.

Key Terms
