



# Foundations of Climate Change: What Is Climate Change?

# 1

## ■ Learning Objectives

After completing this reading you should be able to:

- Define climate change and differentiate between weather and climate.
- Know the general trends of modern climate change, such as observed surface temperature, sea ice coverage, etc.
- Describe how the earth's climate has changed over long periods of time and explain different methods for measuring non-anthropogenic climatic changes.
- Differentiate between human-induced and natural climate changes.
- Explain the earth's energy balance, greenhouse effect, and radiative forcing. Understand how each affect the climate.
- Explain human attribution to increases in atmospheric CO<sub>2</sub> and modern warming.
- Know the primary greenhouse gases (and aerosols), their sources, and relative contribution to climate change.
- Understand the implications of different greenhouse gas global warming potentials as well as atmospheric lifetimes.
- Identify economic and ecological climate impacts (e.g., precipitation, sea level rise). Understand the distribution of these impacts across geography and time as well as their change in frequency and intensity.
- Understand contributors to sea level rise as well as the ocean's unique role balancing the climate cycle.

- Describe extreme-event attribution science and the data and techniques scientists use to connect climate change to extreme events.
- Describe how climate tipping points could disrupt natural systems and harm human well-being.
- Explain the different approaches and key considerations of climate change adaptation.
- Discuss trends in the energy system and how energy sources can contribute to or mitigate climate change. Understand relative carbon intensities of energy sources.
- Identify opportunities and strategies for renewable and low-emissions energy technology (including carbon capture and storage) to act as climate mitigants. Discuss specific challenges (e.g., intermittency) deploying each technology.
- Understand the opportunities and drawbacks of implementing geoengineering techniques to combat climate change.
- Define carbon budget and discuss emissions trajectories to stay within mitigation targets.

Climate change is one of the most important issues of our generation and future generations. Choosing how to respond requires both a knowledge of the science as well as an understanding of our policy options. This chapter will give a brief summary of these two aspects of the climate problem.

A simple analogy to explain the difference between weather and climate involves tossing a six-sided die. The day's weather is the result of a single roll of the weather die. Climate is the statistics from many rolls of the die. You can determine the climate simply by *looking at the die*—you do not have to roll it. If, for example, you see that hot temperatures appear on three sides of the die and cold temperatures appear on the other three, then you can infer that hot and cold temperatures are equally likely.

When we talk about climate, temperature is the most commonly referred to quantity, but there are many other quantities such as precipitation, humidity, cloudiness, visibility, and wind that tell the full climate change story. Because there is a lot of day-to-day and year-to-year variability in the weather, the climate is typically estimated from the statistics of the weather over a period of several decades, typically 30 years.

Climate change describes the long-term differences in the statistics of weather patterns measured over multi-decadal periods. For example, if the average temperature of a city during the period 1990–2020 is warmer than the average temperature during the period 1900–1930, then we can say that the climate changed between these periods. If we go back to our weather dice analogy, climate change means that the dice are changing. As the climate warms, for example, we would find that hot temperatures now appear on more sides of the temperature die. Note that cold temperatures can still occur in a warmer climate—but not as often.

Climate change is sometimes referred to as global warming. In its most literal sense, someone might think global warming only refers to increasing temperatures, while climate change also includes changes in all other aspects of the climate (e.g., precipitation, sea level). In practice, however, most people use the two terms interchangeably.

## INTRODUCTION TO THE PROBLEM

Weather refers to the exact state of the atmosphere at a particular location and time. So, if you tell someone that the current temperature outside is 55°F/13°C, you're talking about the weather. Climate refers to the long-term patterns or statistics of the weather. If you hear that the average daily high temperature for your city in August is 84°F/29°C, that's climate.

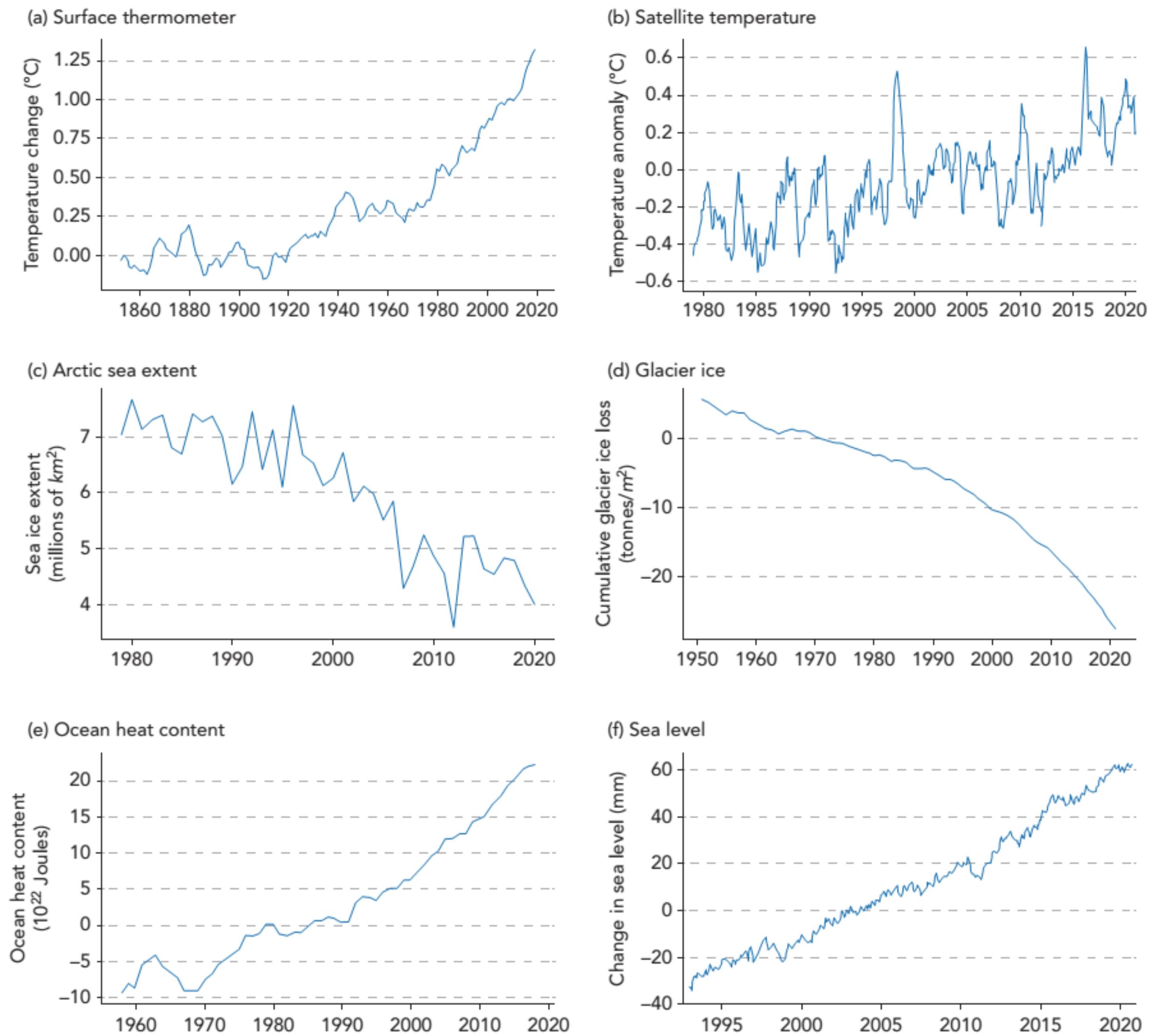
## OBSERVATIONS OF CLIMATE CHANGE

### 1.1 Modern Climate Change

While we have a greater number of high-quality weather observations in more recent years, we have an adequate observational history of the last 150 years covering enough

of the planet that we can measure climate change over that period. Figure 1a shows change in global average temperature since the late-nineteenth century, estimated from

thermometers distributed across the planet. The surface thermometer record shows that the Earth has warmed by  $1.1^{\circ}\text{C}$  over this time (calculated as the difference between



**Figure 1** (a) Global annual average temperature ( $^{\circ}\text{C}$ ), relative to the 1850–1900 average; data have been smoothed to remove short-term variability. (b) Satellite measurements of the global monthly average temperature anomaly ( $^{\circ}\text{C}$ ), relative to the 1991–2020 period. (c) Arctic sea-ice extent (in millions of square kilometers) in September of each year. (d) Global average cumulative mass change of the world's glaciers, tonnes/ $\text{m}^2$ . (e) Ocean energy content (Joules) of the top 2000 m of the world ocean, relative to the 1979–1994 mean. (Boyer, Tim P.; Smolyar, Igor V., et al. [2018]. *World Ocean Atlas 2018*. NOAA National Centers for Environmental Information.) (f) Global-average sea level change, measured by satellite-borne instruments, in millimeters. The seasonal cycle has been removed.

the 1850–1900 average and the 2009–2018 average). As of early 2021, the warmest year in the record was 2016 followed by 2020, 2019, 2017, and 2015.

Figure 2 shows how the warming in Figure 1a is distributed across the planet. The warming is not uniform—land warmed more than the ocean and the northern hemisphere warmed more than the tropics or the southern hemisphere. This is important because about 85% of the world's population lives on land in the northern hemisphere, meaning that they have experienced more warming over the past 150 years than the global average warming seen in Figure 1a.

The data in Figures 1a and 2 have been independently verified. Several independent scientific groups have generated their own surface temperature record (for example, NASA, NOAA, and the UK Hadley Center) from the raw station data, and these all show similar warming. In addition, several of the groups publicly released the code and data used to generate their estimates of warming in order to be transparent with the data and the analyses that were done. This allows anyone to be an independent reviewer of the data and analyses; however, there have not been any legitimate issues in the data or analyses found.

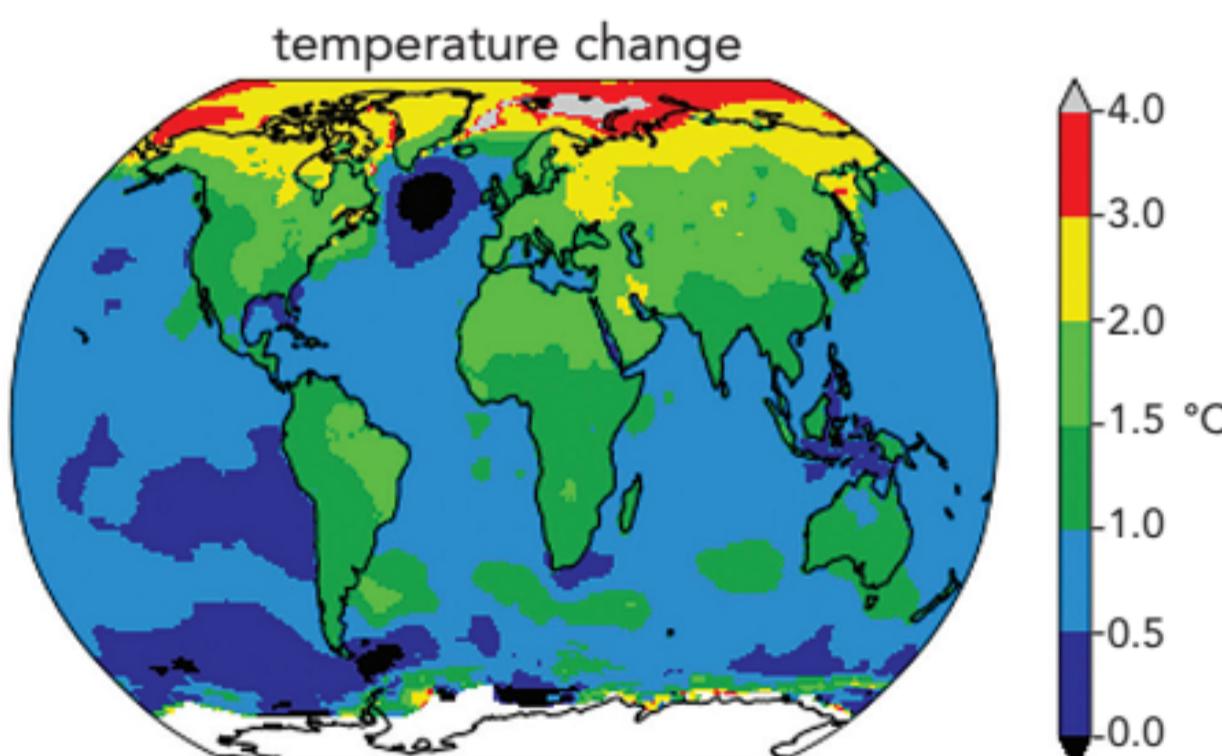
Nevertheless, any sample of data (the temperature observations at observational sites) from the true population (the true temperature change everywhere over all time) may

contain biases or other data issues that the scientific community has not yet recognized. For this reason, scientists look for a comprehensive analysis with multiple independent confirmations of important scientific conclusions. As described below, there are many data sets that confirm the warming seen in the surface thermometer record.

The trend in the global-average temperatures measured by instruments onboard satellites during the period of overlap (Figure 1b) agrees well with that in the surface temperature record (Figure 1a). We can also look at indirect evidence of warming, that is, the effects that warming would cause our planet to experience. Figures 1c and 1d show that ice on the planet is disappearing—something we would expect in a warming climate.

About 93% of the heat trapped by greenhouse gases goes into heating the oceans, so we can also look to see if energy, or heat, is accumulating in the oceans (IPCC, 2013). Figure 1e shows the heat content of the top 2 km/1.25 miles of the ocean, and it shows that the oceans are gaining energy. Finally, Figure 1f shows that sea level is rising fairly linearly. There are two key contributing factors to the rise in sea level. One contributor is the melting of grounded ice. When it melts and the water runs into the ocean, the total amount of water in the ocean increases and sea level rises. Figure 1d shows that we are losing grounded ice on the planet, and we expect that to drive an increase in sea level. Second, water, like most things, expands when it warms. Figure 1e shows that the oceans are indeed heating, and the resulting thermal expansion should also raise sea level. These two processes have contributed about equally to sea level rise over the past century.

Putting all of this evidence together, recent reports from the Intergovernmental Panel on Climate Change (IPCC) have described the confidence in the warming of the climate system since the early twentieth century as unequivocal, meaning beyond doubt. This arises because the conclusion is supported by many independent data sets and statistical analyses, and there is no single error or confounding factor that would generate a false warming trend in all of them. As a result of this consistency, there is virtually no chance that enough of these data sets could be wrong by far enough, and all in the same direction, that the overall conclusion that the climate is currently warming is wrong.



**Figure 2** The distribution of modern warming (in °C). Warming is calculated as the difference between the 1850–1900 average and the 2009–2018 period.

## 1.2 Climate Change before Humans

To put today's warming into context, it is useful to consider the Earth's entire climate history. The measurements described in the previous section go back at most 170 years, so a different strategy is required to look further back in time without the same types of observational systems (i.e., thermometers). What we need are long-lived, geological, chemical, or biological systems that have the climate imprinted on them. Then, we can make measurements today that provide evidence what the climate was like *in the past*.

For example, scientists can extract climate information from tree rings. Tree growth follows an annual cycle, which is imprinted in the rings in their trunks. As trees grow rapidly in the spring, they produce light-colored wood; as their growth slows in the autumn, they produce dark wood. Because trees grow more and produce wider rings in relatively warm and wet years, the width of each ring yields information about temperature and precipitation around that tree in that year. Scientists today can measure the size of the rings of a tree and then estimate the local climate around the tree for each year during which the tree was alive.

There are many different proxies that cover different regions and different time frames. For example:

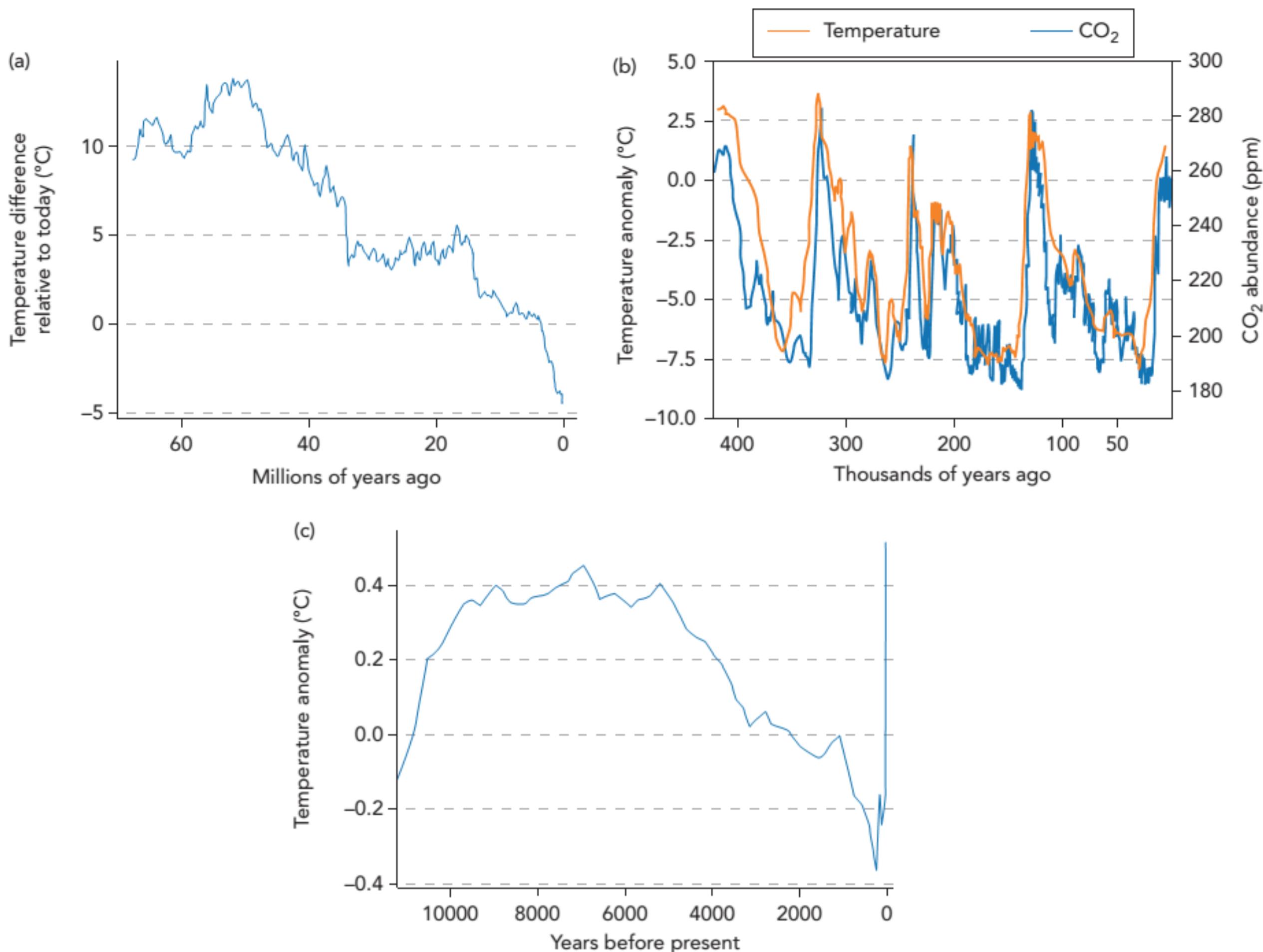
- Tree rings: These measurements can reveal climate variations in regions where trees grow and experience seasons for the last millennium.
- Corals: Analysis of the skeletons of these sea creatures can yield climate conditions in the ocean over millions of years.
- Speleothems: These cave structures can yield estimates of the climate in the region around the cave over the past few hundred thousand years.
- Ice cores: Measuring the chemical composition of ice (mainly in Greenland and Antarctica) yields estimates of the climate over the past million years or so.
- Ocean sediment cores: Analyzing the composition of the mud at the bottom of the ocean provides information about the climate covering the past tens of millions of years.

Figure 3a shows the temperature over the past 70 million years. About 50 million years ago, the Earth was much warmer than it is today—so much so, in fact, that there was no permanent ice on the planet. Since then, the climate has generally been cooling.

Figure 3b shows the last 410,000 years, and it shows that the planet has been cycling between cold periods, known as ice ages and interglacials (warmer periods). These cycles take approximately 100,000 years to complete. The last ice age reached its coldest point about 20,000 years ago, and it ended about 10,000 years ago, and, since then, we have enjoyed a rather pleasant interglacial period.

Figure 3c shows the last 11,000 years, since the end of the last ice age, a period known as the Holocene. This estimate shows that temperatures peaked about 7,000 years ago and then started a slow, long-term decline that bottomed out in a period 200 to 300 years ago, known as the Little Ice Age. After that, the Earth began warming, and in the late 2010s, it was about 1°C warmer than the Little Ice Age—roughly comparable to peak temperatures of the mid-Holocene.

These estimates of the Earth's past climate allow us to reach several important conclusions about the modern warming we are presently experiencing. First, the global average temperature difference between an ice age and an interglacial is about 6°C, so the 1°C warming the Earth has experienced since the nineteenth century is not an insignificant amount of warming. In addition, human society, made up of mega-cities and concrete and iron infrastructure on a global scale, has only been around since the industrial revolution (around 1800) and, since that time, the range of global temperatures our society has experienced is small. As our climate continues to warm, we will soon be departing from conditions under which human society developed and thrived. More troubling, the warming we are experiencing is very rapid. For example, the warming over the past century (approximately 1°C in about a century) is around 16 times faster than the average rate of warming coming out of the last ice age (roughly 6°C in 10,000 years corresponds to an average warming of 0.06°C/century).



**Figure 3** (a) Reconstructed global average surface temperature over the past 70 million years, relative to today's temperature. (b) Temperature of the southern polar region (solid line) over the past 410,000 years, relative to today's temperature, constructed from an Antarctic ice core. Carbon dioxide (dotted line) is from air bubbles trapped in the ice. (Petit, J. R., D. Raynaud, C. Lorius, et al., "Historical isotopic temperature record from the Vostok ice core", in *Trends: A Compendium of Data on Global Change* [Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, 2000], doi: 10.3334/ CDIAC/ cli.006.) (c) Global temperature of the last 11,000 years, relative to the 1961–1990 average, based on multiple proxy records (Westerhold et al., 2020; CDIAC; Marcott et al., 2013).

## CAUSES OF CLIMATE CHANGE

### 1.3 Energy Balance

The source of energy for the Earth's climate is sunlight, which is mainly visible radiation and provides about  $340 \text{ W/m}^2$  of energy to the Earth (that's a global and annual average). About 30% of this incoming sunlight is

reflected back to space by clouds and other reflective elements of the climate system, meaning that net solar energy absorbed by the surface of the Earth is  $238 \text{ W/m}^2$ . In the 1820s, Joseph Fourier recognized that this meant that the Earth had to also be radiating an equal amount of energy back to space. This radiation back to space is in the form of infrared radiation, but for this analysis consider it heat.

The amount of energy radiated by an object is determined by the temperature of the object—as the object heats up, it radiates more energy. This means that the amount of heat radiated by the Earth to space is determined by the temperature of the planet. So for a given amount of energy from the Sun, there is a temperature of the planet that will give you an equal amount of energy radiated back to space.

This is the most important rule of the Earth's climate: energy balance. The energy reaching the Earth from the Sun must be equal to the energy the Earth radiates back to space, and this determines the temperature of the climate system.

## 1.4 The Greenhouse Effect

It turns out that the temperature of the planet is not the only thing that determines the amount of energy the Earth radiates to space. The composition of the atmosphere also matters—in particular, the amount of greenhouse gases in the atmosphere. Greenhouse gases are a part of the atmosphere that absorbs infrared radiation (or radiant heat). In the 1820s, Joseph Fourier recognized that these gases reduced the amount of power the Earth radiated to space, so a planet with more greenhouse gases in the atmosphere must be warmer than one without. This is what scientists mean when they talk about a greenhouse effect.

As the mass of greenhouse gases in our atmosphere increases, the atmosphere traps more heat, leading to higher temperatures. This possibility was first recognized by scientists more than a century ago, first by the Swedish chemist Svante Arrhenius in 1896 and again, with more supporting evidence by the British engineer Guy Callendar, in 1938.

Merely having an atmosphere does not produce a greenhouse effect; the atmosphere needs to have the right composition to absorb infrared radiation. On Earth, the majority of the atmosphere consists of molecular nitrogen ( $N_2$ ), oxygen ( $O_2$ ), and the inert gas argon ( $Ar$ ). These simple molecules do not interact with infrared radiation and therefore generate no greenhouse effect to warm the surface. Rather, the greenhouse effect is caused mainly by minor constituents in the atmosphere: water vapor ( $H_2O$ ), carbon dioxide ( $CO_2$ ), and other components like methane that we will learn about later.

Water vapor is the most important greenhouse gas in the atmosphere—meaning it traps the most heat—and carbon

dioxide is the next largest contributor. Carbon dioxide's strong contribution occurs despite the fact that it made up only 0.0415% of our atmosphere in 2020. This is an awkwardly small number, so the concentration is usually written as 415 parts per million (ppm), meaning that, in every million molecules of air, about 415 molecules are  $CO_2$ .

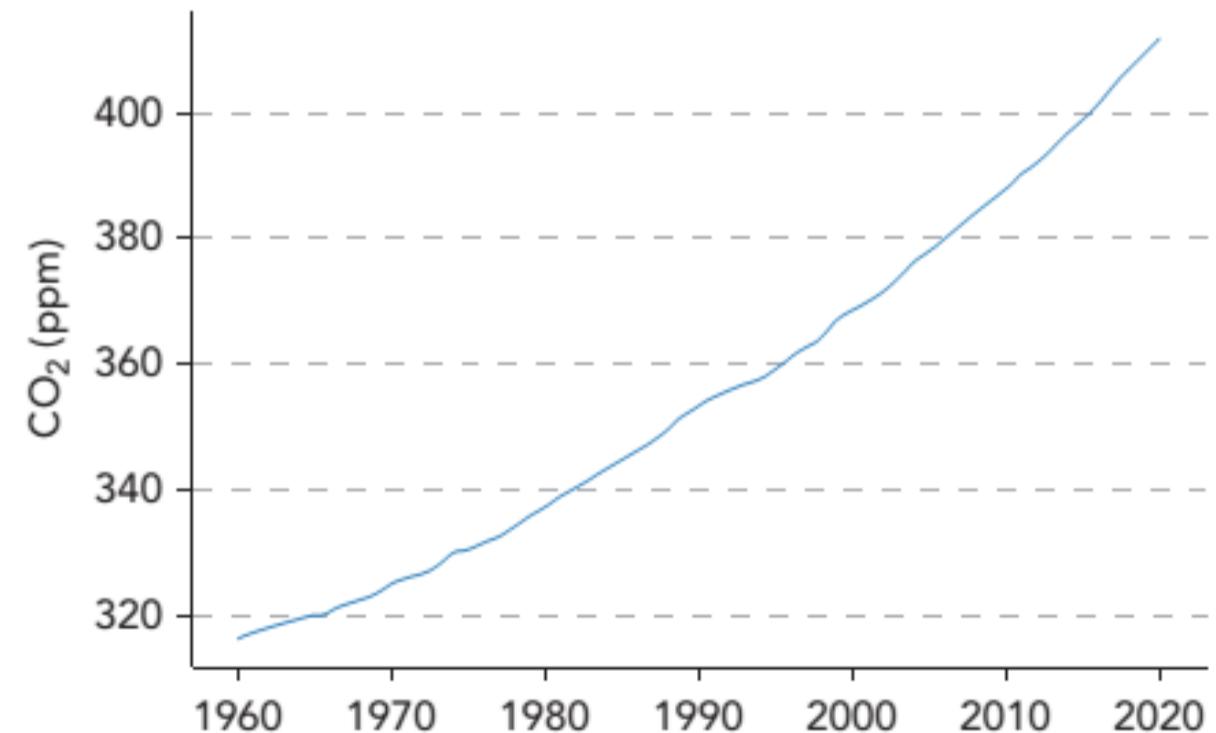
## 1.5 How Humans Are Changing the Climate

We saw in the previous section how the Earth's climate is determined by the amount of greenhouse gases in the atmosphere. In this section, we discuss the evidence showing that greenhouse gases in our atmosphere are increasing as a result of human activity.

### 1.5.1 Carbon Dioxide

We have been directly monitoring the abundance of carbon dioxide in the atmosphere since the middle of the twentieth century. The measurements are plotted in Figure 4, which is often referred to as the Keeling Curve after Charles D. Keeling, the scientist who initiated the measurements in 1957. The measurements clearly show a long-term upward trend. As we discussed in the last section, we can therefore expect that the climate should be warming—and, as we saw in Section 1.1, it is.

This increase in carbon dioxide is primarily due to the combustion of fossil fuels. This conclusion is confirmed from



**Figure 4** The record of atmospheric carbon dioxide since the middle of the twentieth century. (Dr. Pieter Tans, NOAA/GML [[gml.noaa.gov/ccgg/trends/](http://gml.noaa.gov/ccgg/trends/)] and Dr. Ralph Keeling, Scripps Institution of Oceanography [[scrippsc02.ucsd.edu/](http://scrippsc02.ucsd.edu/).])

multiple sources of data. If we look at carbon dioxide concentration in our atmosphere over the last few centuries (not shown), we see that carbon dioxide began increasing at the beginning of the nineteenth century, at the same time the world economy began generating energy from fossil-fuel combustion (IPCC, 2007).

Scientists have observed that, for the past 50 years, the increase in carbon dioxide in the atmosphere each year averages 44% of what humans released into the atmosphere in that year (Global Carbon Project, 2020). The reason for this is that about one quarter of the emitted carbon dioxide is absorbed into the ocean and leads to ocean acidification, which we will discuss later in this chapter. Emitted carbon dioxide is also absorbed by the land biosphere by enhanced plant growth. Ultimately, a bit less than half of what humans emit stays in the atmosphere each year.

The fact that the increase in atmospheric carbon dioxide each year is (on average) a fixed fraction of what human's emit is one of the key pieces of evidence that the increase in atmospheric carbon dioxide is due to human activities. If the increase were due to some non-human process, it seems unlikely that it would track human emissions so closely.

The chemical composition of atmospheric carbon dioxide also shows that the increase in Figure 4 is due to fossil-fuel combustion. The analysis is based on isotopes of carbon. All carbon atoms have six protons, but carbon atoms can have different numbers of neutrons, which are called isotopes. The most abundant isotope is carbon-12, containing six neutrons to go with the six protons, but less abundant isotopes include carbon-13, with seven neutrons, and carbon-14, which has eight neutrons.

The potential sources of carbon dioxide (e.g., volcanoes, fossil fuels, etc.) release carbon dioxide with different amounts of these various isotopes. Chemical analysis of the atmosphere shows that the carbon dioxide being dumped into the atmosphere over the past half century has an isotopic composition that is consistent with carbon dioxide from fossil fuels.

By looking at air bubbles trapped in glacial ice, we can measure chemical composition of atmospheric carbon dioxide back through time. These measurements tell us that, in the late-eighteenth century, before the industrial revolution, there was about 280 ppm in the atmosphere. By 2020,

humans have increased atmospheric carbon dioxide by 135 ppm, or about 45%.

### 1.5.2 Other Greenhouse Gases and Aerosols

Water vapor and carbon dioxide are the most important heat-trapping greenhouse gases, but they are not the only ones. The next most important greenhouse gas is methane ( $\text{CH}_4$ ), which has increased from 0.8 ppm before the industrial revolution to about 1.9 ppm in 2020. This might seem like a small increase, particularly compared to the 130-ppm increase in carbon dioxide, but methane is a far more powerful greenhouse gas on a per molecule basis—each kilogram of methane traps as much heat as 28 kilograms of carbon dioxide. This heat-trapping power relative to carbon dioxide is known as the global warming potential (GWP), and its value has important policy implications. For example, methane's GWP of 28 means that it is better for the climate to reduce emissions of one tonne of methane than it is to reduce one tonne of carbon dioxide.

Human activities are also increasing the atmospheric abundance of other powerful greenhouse gases, such as nitrous oxide ( $\text{N}_2\text{O}$ ) and an entire class of molecules called halocarbons. These gases are found at very low concentrations in our atmosphere—parts per billion—but they have large GWPs (Table 1), so that even small increases can trap a significant amount of heat in our climate system.

Finally, there is ozone ( $\text{O}_3$ ). This molecule is best known for its ability to absorb ultraviolet radiation that, if it reached the surface, would have deleterious impacts on human and natural ecosystems, but it is also a powerful greenhouse gas. Humans do not directly emit ozone into the atmosphere, but they emit ozone's precursors (hydrocarbons and oxides of nitrogen), which react in the atmosphere to form ozone. Over the past few decades, increases in these precursors have led to increases in ozone, which has led to more trapping of heat.

Another way that humans are changing the climate is through emissions of aerosols or their precursors. Aerosols are particles so small that the buoyant forces can be stronger than the force of gravity and therefore remain suspended in the atmosphere for days or weeks. Aerosols can affect planetary energy balance because aerosols reflect incoming solar radiation back to space, so their net effect is to cool the climate. They also can affect cloud formation

**Table 1** Metrics of major greenhouse gases. Increases in abundance and fraction of heating for the years 1750–2010. GWPs are calculated assuming a 100-year time horizon. (IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.)

Species	Atmospheric Lifetime	Global Warming Potential (GWP)	Increase in Abundance Since Pre-Industrial	Fraction of Total Greenhouse Radiative Forcing
Carbon dioxide	500 years	1	130 ppm	56%
Methane	12.4 years	28	1.1 ppm	15%
Nitrous Oxide	121 years	265	75 ppb	5%
Halocarbons	Years to millennia	100s to 1000s	A few ppb	11%
Ozone	Weeks to months	N/A	Tens of ppb in the upper troposphere	12%

Note: ppb = parts per billion (how many molecules of the species there are in every billion molecules of air). Carbon dioxide is removed from the atmosphere on several time scales. The lifetime in the table is the time to remove 75% of the emissions. Ozone does not have a GWP because of its short atmospheric lifetime.

and make clouds more reflective, which is an additional cooling mechanism.

As a result of human activities over the past two centuries, the abundance of these aerosols has increased, and this has generated a cooling effect that tends to partially offset the warming effect of the increase in greenhouse gases. As an example of how humans generate aerosols, when fossil fuels containing sulfur impurities are burned, the sulfur is released into the atmosphere with the other products of combustion. Once in the atmosphere, the sulfur gases react with other atmospheric constituents to form small liquid droplets known as sulfate aerosols. Other types of aerosols produced by humans include black carbon aerosols, such as soot, which is produced by such things as the incomplete combustion of a smoldering fire or two-stroke gasoline engines. Mineral dust is produced by agricultural activities (e.g., harvesting, plowing, overgrazing), changes in surface water features (e.g., drying out of lakes such as the Aral Sea in Central Asia and Owens Lake in the Western US), and industrial practices (e.g., cement production).

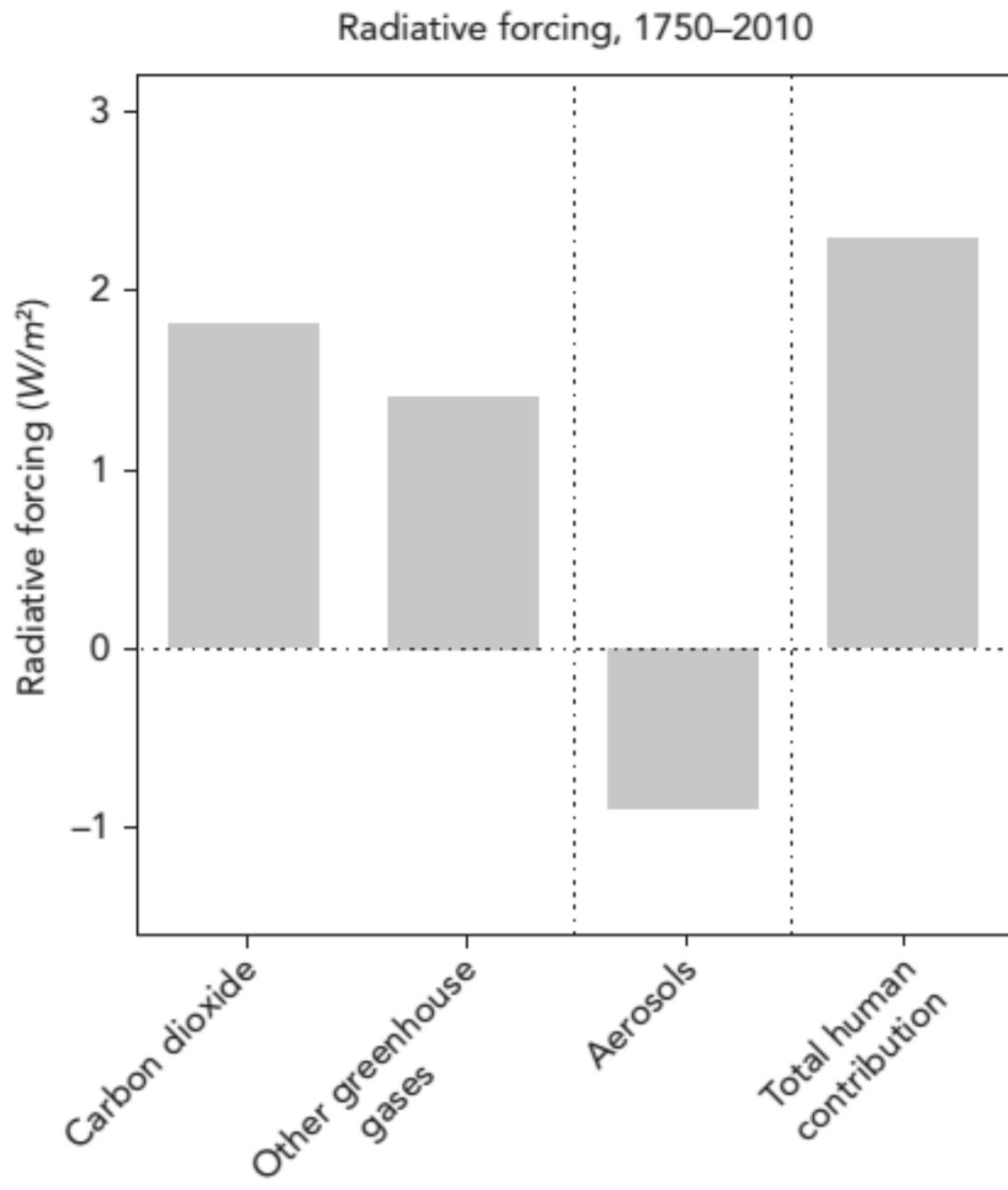
### 1.5.3 Summarizing The Human Impact on Our Climate

In the past 250 years, the Earth has experienced significant anthropogenic changes to radiative forcing, which

quantifies the difference between the incoming energy (sunlight) absorbed by the Earth and the outgoing energy (infrared radiation) emitted by the Earth back to space. Carbon dioxide and other greenhouse gases have caused a combined positive (heating) change to radiative forcing of about  $3 \text{ w/m}^2$ , while aerosols have caused a negative (cooling) change to radiative forcing of about  $0.75 \text{ w/m}^2$  (IPCC, 2013). The net human contribution is therefore about a positive  $2.25 \text{ w/m}^2$ , which is illustrated in Figure 5.

You might be wondering why water vapor does not appear in Figure 5, particularly because it was stated that it was our climate system's most important greenhouse gas. The main source of water vapor in the atmosphere is evaporation from the oceans, and it is primarily removed from the atmosphere when it falls out as rain or snow. Because the amount of water vapor in the atmosphere is regulated by evaporation and condensation, it is fundamentally set by the Earth's temperature—if the Earth warms, the amount of water vapor in the atmosphere increases. If the Earth cools, the opposite happens and the amount of water vapor in the atmosphere decreases. Emissions of water vapor directly from human activities contribute essentially nothing to its atmospheric abundance.

Water vapor's abundance in the atmosphere is set by the temperature, and therefore water vapor's main role in climate change is to amplify changes caused by things like increasing



**Figure 5** Radiative forcing caused by changes in the climate between 1750 and 2010. Values are adapted from the IPCC's Fifth Assessment Report. (IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.)

carbon dioxide through a process referred to as the water vapor feedback. This arises because a warmer atmosphere can hold more water vapor. Thus, an initial warming leads to increased atmospheric humidity, and because water vapor is itself a greenhouse gas, this leads to additional warming, and that feeds back to increase the humidity. This is an important process in our atmosphere, and it has the capacity to double, or even triple, the amount of warming we get from carbon dioxide alone (Dressler, 2013).

## 1.6 Attribution of Modern Warming

In Section 1.2, you saw that the climate is a dynamic system that has experienced changes in cyclical patterns over the past thousands and millions of years. Here, we first describe

all of the mechanisms that are known to change the climate. We will then assess the evidence of human influence for each mechanism and identify the one that is most likely responsible for the majority of climate change.

Here are the natural processes that can affect the climate:

- **Tectonic processes:** The Earth's continents are moving and, over tens of millions of years, this continental drift can substantially alter the arrangement of the continents across the Earth's surface. Such changes can lead to changes in the climate through several mechanisms. For example, the movement of a continent toward the poles can lead to the growth of an ice sheet on the continent. Because ice sheets are reflective, the growth of a continental ice sheet will lead to more incident sunlight being reflected back to space, which will tend to cool the climate. However, this process is exceedingly slow—the movement of the continents occurs over geologic time scales, millions of years. Thus, this cannot be responsible for modern warming because it is simply too slow.
- **Output of the Sun:** The ultimate energy source for the climate system is the Sun. The observed warming trend could be explained if the Sun had been getting brighter over the last two centuries. Scientists have been directly measuring the output of the Sun since the late 1970s, and there is no long-term trend that could explain the very rapid warming over that period. Prior to that time, it was more difficult to determine what the Sun was doing because there were no satellite measurements. Instead, the Sun's output for this period must be inferred indirectly from other measurements, such as the number of sunspots, which people have counted for many hundreds of years, or from chemical proxies such as the carbon-14 content of plant material. Such estimates suggest that the Sun has changed little over the past few hundred years. Thus, we can eliminate this as a cause of modern global warming.
- **Orbital variations:** The amount of solar energy reaching the Earth is determined not only by the energy emitted by the Sun but also by the Earth–Sun distance. If, for example, the Earth moved closer to the Sun, then the solar energy hitting the Earth would increase even if the thermal properties of the Sun did not change. In fact, the Earth's orbit does change in three ways: First, the shape of the orbit changes, with the orbit cycling between more elliptical and less elliptical over a period

of 100,000 years. Second, the tilt of the Earth, today about  $23.5^\circ$ , cycles from  $22.3^\circ$  to  $24.5^\circ$  over a period of about 41,000 years. Third, the date of closest approach of the Earth to the Sun, presently occurring in January, cycles through the calendar over a period of about 23,000 years. These variations are responsible for the ice ages (Figure 3b), but could not be the cause of modern warming because the orbit does not change much over a century.

- **Unforced variability:** The previous suspects are all examples of climate change forced by planetary energy imbalances. However, the Earth's climate system is so complex that it can also vary without an imposed energy imbalance driving it. Such changes, which are caused by complex internal physics of the climate system, are often referred to as unforced variability. The best-known example of unforced variability in our climate is the El Niño/Southern Oscillation (referred to by scientists by its initials, ENSO). El Niño events, which make up the warm phase of ENSO, occur every few years and last a year or so, and typically alternate with cooler La Niña events. Could the modern warming be due to unforced variability? It is very unlikely for three reasons: First, there is no theory that explains the warming for the period of time since the industrial revolution, nor observations supporting unforced variability as causing changes to global temperatures. Second, observations of the past millennium show nothing similar to the rate and magnitude of warming of the twentieth century. Third, computer simulations of the climate do not support this as a cause. Thus, scientists are very skeptical that unforced variability is playing anything other than a minor role in modern warming.
- **Greenhouse gases:** The evidence supporting the cause of the warming being the increase in greenhouse gases over the last two centuries is immense. First, the laws of physics tell us that adding carbon dioxide, or any other gas that absorbs infrared radiation, to the atmosphere should warm the planet by affecting the planet's energy balance. Second, it is a fact that humans are adding carbon dioxide to the atmosphere. Just based on that, you could have predicted the warming of the climate that we are observing. The timing of warming, beginning in the nineteenth century, after the industrial revolution, and the magnitude of the warming, also match scientific

theory. Finally, the geologic record shows that changes in climate are frequently associated with changes in greenhouse gases. For example, carbon dioxide changes during ice-age cycles (Figure 3b) are thought to play a key role in amplifying the size of the climate variations, although the exact mechanism that alter the concentration of atmospheric carbon dioxide during ice-age cycles is an active area of research.

## 1.7 Summary Statement on Attribution of Modern Warming

Given the evidence supporting the hypothesis that greenhouse gases are responsible for the modern warming and the lack of support for any competing theory, there is widespread agreement in the scientific community on the reality of anthropogenic (human) influence on the climate system. The 2013 report of the Intergovernmental Panel on Climate Change came to the following conclusion:

It is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together.

Note that this statement is carefully caveated in three ways:

- The phrase *more than half*: This makes it clear that greenhouse gases are responsible for a majority of modern warming, but not necessarily 100%.
- The specified time period, 1951–2010: It is only during this period that our observations are sufficient to rule out alternative explanations for the warming. It is certainly possible that greenhouse gases were the dominant cause of the warming prior to this period, but that cannot be proven to the high standards required by the scientific community.
- The words *extremely likely*: The Intergovernmental Panel on Climate Change uses a set of carefully defined terms to express confidence. In the parlance of the IPCC, *extremely likely* denotes a confidence of 95%. This acknowledges that the mainstream scientific view may indeed be wrong (unlike the evidence that the globe is warming, which the IPCC describes as *unequivocal*). However, the chance is small—less than 1 in 20.

## FUTURE WARMING

### 1.8 Shared Socioeconomic Pathways

In order to predict future climate change, we must first project how much greenhouse gas society will emit in the future. Because of the difficulty of making a single, confident projection of the future, a group known as the Integrated Assessment Modeling Consortium has instead developed a set of alternative pathways that they believe span the range of different futures the world may experience over the next century or two. These are based on five different narratives of the future, which are referred to as *Shared Socioeconomic Pathways*, usually abbreviated SSPs.

The SSPs are labeled SSP1, SSP2, SSP3, SSP4, and SSP5, and they each represent a different way the world may evolve in the future. Note that the numbers 1–5 in the name do not correspond to any particular parameter in the scenarios; rather, they are arbitrary labels assigned to each scenario. Furthermore, SSP4 is rarely used in the climate literature, and we will not consider it further.

One can think of these different scenarios as mainly differing in the amount of economic growth and the amount of climate-safe energy that is being deployed (Figure 6a), which leads to different amounts of carbon dioxide emitted into the atmosphere each year (Figure 6b). Given these emissions scenarios, the resulting atmospheric concentrations of carbon dioxide can be calculated (Figure 6c) and, from this, the amount of climate change under each scenario can be estimated by inputting atmospheric carbon dioxide into a computer simulation, known as a global climate model, sometimes referred to by its initials as a GCM (Figure 6d).

The different scenarios describe very different worlds:

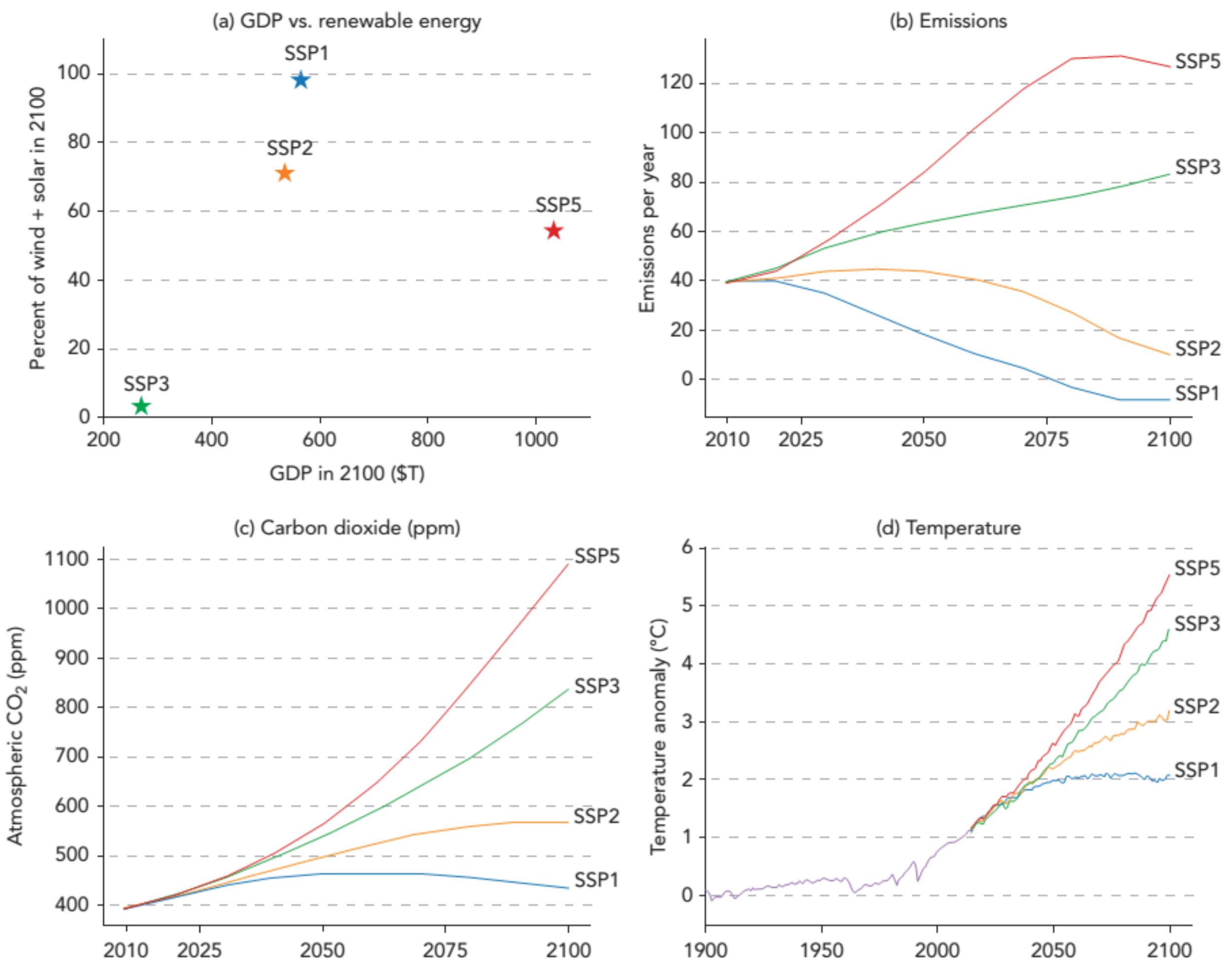
- SSP1 is a sustainable world where the world's economies gradually shift towards a more environmentally friendly path. Because of strenuous efforts to adopt renewable energy, emissions are currently peaking and expected to decline throughout the rest of the century. In fact, SSP1's emissions go negative around 2075, meaning that humans are pulling more carbon out of the atmosphere than they are releasing. The low emissions associated

with this scenario lead to temperature increases of 2°C/3.6°F above the pre-industrial climate.

- SSP2 is a world that follows the trends of our world today, leading to generally declining emissions over the twenty-first century due to widespread adoption of renewable energy (although slower than in SSP1). Economic growth is similar to SSP1. The carbon dioxide emissions associated with this scenario lead to temperature increases of 3°C/5.4°F above the pre-industrial climate.
- SSP3 is a world where economic inequality gets worse, leading to increasing conflict between regions. Because of this, economic growth is slow and adoption of new energy technology is also slow, leaving the world almost entirely dependent on fossil fuels. The combination of these leads to carbon dioxide emissions increasing throughout the century, reaching around double today's values in 2100. Temperature increases in this world are 4.5°C/8°F above the pre-industrial climate.
- SSP5 is a world similar in many ways to SSP1, but it is one that emphasizes economic growth rather than sustainability. As a result, economic growth in this world is very high and fossil fuels power a significant fraction of this growth. This leads to carbon dioxide emissions increasing throughout the century, reaching more than triple today's values in the late-twenty-first century. Temperature increases in this world are 5.5°C/10°F above the pre-industrial climate.

No one knows which emissions trajectory will turn out to describe reality because emissions will be determined by political decisions that have not yet been made. However, it seems likely that real emissions will fall somewhere in the range defined by these scenarios, so you can expect that our future climate will be similarly constrained.

Figure 6c shows that, while the warming of the next few decades is largely already determined by past investments in fossil-fuel infrastructure and inertia in the climate system, we control the amount of warming experienced during the second half of the twenty-first century, and there is nearly a 4°C difference in temperature between the lowest (SSP1) and highest scenario (SSP5). Because many people alive today might live well into the second half of the century, this has relevance for many people who are alive today, and all future generations.



**Figure 6** (a) GDP in 2100 (trillions of 2005 US dollars) versus the sum of wind and solar capacity as a% of total (final) energy consumption in 2100. (This graph is based on the SSP database hosted by the IIASA Energy Program at <https://tntcat.iiasa.ac.at/SspDb>. Any citations of publications made available through this and related publications are to be made in accordance with best scientific practice.)

(b) Emissions of carbon dioxide (billions of tonnes of carbon dioxide per year). (This graph is based on the SSP database hosted by the IIASA Energy Program at <https://tntcat.iiasa.ac.at/SspDb>. Any citations of publications made available through this and related publications are to be made in accordance with best scientific practice.)

(c) Atmospheric carbon dioxide (ppm). (This graph is based on the SSP database hosted by the IIASA Energy Program at <https://tntcat.iiasa.ac.at/SspDb>. Any citations of publications made available through this and related publications are to be made in accordance with best scientific practice.)

(d) Computer simulations of global and annual average surface temperature change under the SSP scenarios. Temperatures prior to 2014 are from model runs driven by historical forcing. (Eyring, V., Taylor, K. E., et al. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* 9 (5), 937-1958, doi:10.5194/gmd-9-1937-2016.)

## 1.9 Impacts of This Climate Change

A few degrees of global-average warming over the next century would have significant impacts to life on Earth. Although the local temperatures can vary considerably, the global average temperature of the Earth is very stable, with stochastic variations of just a few tenths of a degree per year. Moreover, seemingly small changes in global average temperature are associated with massive shifts in the Earth's climate. For example, the global annual average temperature during the last ice age was about 6°C colder than that of our present climate. At that time, glaciers covered much of North America and Europe and, because so much water was tied up in glaciers, sea level was approximately 100 m (330 ft) lower than it is today. The net effect of all of these changes was a completely different distribution of ecosystems.

Thus, warming of a few degrees Celsius over the coming century (Figure 6d), comparable to the warming since the last ice age, implies enormous changes in our environment. This would be bad for human progress because humans are adapted to our present climate. We have built trillions of dollars of infrastructure in places where it makes sense in today's climate. We invest in agricultural infrastructure in regions that today are good for farming. We build cities at today's sea level. We construct storm water infrastructure to handle storms that occur today. If the climate changes, these assumptions will no longer make sense. We will have to rebuild agricultural infrastructure in new regions where agriculture makes sense in a changed climate, we will have to build coast defenses or relocate cities in response to higher seas, and we will have to enhance our infrastructure to handle more intense storms.

Not every single change in every region will be negative. Warmer cold-season temperatures might have benefits: less cold-weather mortality, benefits to agriculture of fewer freezing events that can destroy some crops. Plant growth may well be enhanced in some regions. But these positive effects are expected to be outweighed by the more pervasive negative effects. Examples of negative impacts of warmer cold-season temperatures include less wintertime insect mortality, leading to increased agricultural damage from pests, or less wintertime precipitation falling as snow, reducing snowpack and meltwater and stressing freshwater supplies during the spring and summer.

### 1.9.1 Temperature

One of the most certain predictions of climate science is that the long-term trajectory of the climate is towards warmer temperatures. However, an important consideration is that the warming will not be uniform across the globe. In a continuation of the observed patterns seen in Figure 2, we expect continents to warm more than oceans and to have more warming in the northern hemisphere than in the southern. Given that most people live on land of the northern hemisphere, this means that the average temperature increase experienced by humans will be larger than the global average warming in Figure 6c.

Higher temperatures will have many negative impacts for society. Temperature extremes can be fatal—for example, a 2003 heat wave in Europe caused tens of thousands of excess deaths. Higher temperatures also reduce the productivity of people who have to work outside and, in some regions, temperatures are getting high enough that people cannot work outside in the middle of the day in summer. Higher temperatures, especially when combined with precipitation changes, can reduce agricultural yields.

### 1.9.2 Precipitation

Next to temperature, precipitation is another key aspect of climate. As the surface temperature increases, there is an increase in the rate of evaporation at the surface. Because precipitation must balance evaporation, precipitation must therefore also increase. More quantitatively, total global precipitation is projected to increase by about 3% for every degree Celsius of global average warming (Jeevanjee, 2018).

Although total rainfall is expected to increase, similar to temperature, the increase will not be distributed evenly. Scientists expect regions that get a lot of rain today to get more as the climate warms, while dry regions will become drier, a pattern referred to as "wet gets wetter, dry gets drier."

In addition to changes in the pattern of precipitation, it is likely that a higher fraction of total rainfall will come during the heaviest downpours, which continues a trend observed over the last few decades. This will tend to increase the occurrence of flood events. The increase in the fraction of heavy events also tends to increase the time between rain events, which combined with warmer temperatures, will increase the rate at which water is lost from soils by

evaporation and increase the occurrence of drought. Thus, we get the surprising result that both wet and dry extremes will grow more likely in the future: When it rains, it's more likely to flood, and when it's not raining, it's more likely to create drought conditions.

There will also be shifts in the form of precipitation. Less wintertime precipitation will fall as snow and more will fall as rain. This is more important than it might sound: When snow falls in winter, the water does not run off until the snow melts in spring. Rain, on the other hand, runs off immediately. So changing the form of precipitation will change the timing of runoff, increasing the availability of water in winter and spring and decreasing it in summer.

Changes in precipitation will have negative impacts for society. As with all other aspects of the climate, societies adapt in important ways to the amount and timing of rainfall. Changes will require construction of new infrastructure to protect against flood events in some regions and droughts in others. It may be politically destabilizing as it exacerbates political tensions over access to water.

### 1.9.3 Sea Level & Ocean Acidification

Sea level rise is a direct impact of climate change with the main future driver being the melting of grounded ice. The melt water eventually reaches the ocean, increasing the total amount of water in the ocean and, therefore, sea level. Measurements (e.g., Figure 1f) confirm that sea levels are already rising as temperatures have gone up, and we can be confident that the seas will continue to rise into the next century.

The IPCC's Fifth Assessment Report contains predictions that sea level will rise 45 to 75 cm (18 to 30 inches) above today's levels by 2100. Even though a sea level rise of 45–75 cm may not seem significant, the impacts could be very serious. In Florida, for example, a sea level rise in the middle of the projected range would flood 9% of Florida's current land area at high tide. This includes virtually all of the Florida Keys as well as 70% of Miami-Dade County. It also includes important infrastructure, such as two nuclear reactors, three prisons, and sixty-eight hospitals (Stanton, 2007). And this is just Florida. Multiply these impacts to account for all of the places on the planet where people live near sea level, and you can get a feel for how big a problem this is going to be.

Because ice melts slowly, the amount predicted for this century is just a fraction of how much sea level rise we are committed to. Based on observations of previous changes in climate, it has been estimated that sea level rises a few meters for every degree of warming (Garbe, 2020). This means that a few degrees of warming this century could commit us to many meters of sea level rise. It may take millennia for sea level to fully respond to the warming of the twenty-first century, or it could happen more rapidly in a tipping point scenario (see Section 1.9.5).

Ocean acidification is another consequence of emissions of carbon dioxide to the atmosphere. As discussed earlier, about a quarter of carbon dioxide emitted to the atmosphere by human activities ends up in the oceans where, in the liquid environment of the ocean, carbon dioxide is converted into carbonic acid. The net result is that, as humans continue to emit carbon dioxide to the atmosphere, the oceans absorb more and more, and the oceans will become more acidic.

This can have important impacts on ocean ecosystems. For example, decreasing the ocean's pH makes it harder for calcifying species to build and maintain their shells and skeletons. These species will find it more and more difficult to extract carbonate from the water for use in their shells or skeletons. Eventually, ocean chemistry will increase to the point where it is fatal for these species.

### 1.9.4 Extreme Events

While we've previously been focused on average conditions, some of the biggest impacts of climate change come from the changes in frequency and intensity of extreme weather events. However, when it comes to extreme events, climate change is only one of the contributors as extreme weather events are stochastic, meaning random in time. For example, extreme heat waves are magnified when added on top of the long-term warming. Another example is how strong coastal storms can combine with sea level rise to generate extreme sea level events.

Until recently, it was difficult to quantitatively determine the extent to which climate change played a role in an extreme event. In response to this need, a new branch of climate science known as **extreme-event attribution science** has begun to give us the capability to quantify the contribution of climate change to extreme events.

Extreme-event attribution analyses use three different sources of information. The first techniques uses statistical analysis of historical climate. The observations can be statistically analyzed to determine the likelihood that an observed extreme event occurring today could have occurred prior to human-induced warming. By itself, however, this type of analysis usually can't tell you whether an observed phenomena was caused by global warming or by something else because correlation does not prove causality.

Thus, the second technique focuses on our understanding of the physics of the phenomenon. It should be obvious why, in a warmer world, we expect to get more frequent heatwaves. The clarity of the connection adds to our confidence that climate change is a factor in the occurrence of heat waves. For other things, like the frequency of occurrence of tornadoes, we do not have a good understanding of how this will change as the climate warms. This lowers our confidence that any particular tornado outbreak was affected by global warming.

Finally, we use computer simulations (i.e., GCMs) of the climate to evaluate frequency and intensity of extreme events. The simulations can be run with and without the increase in greenhouse gases, and the impact of climate change can be quantitatively estimated. If we find that a heatwave with the particular characteristics of the observed event rarely or never occurs in the world without climate change, but does in a world with climate change, then it increases our confidence that climate change was a factor in the event. These attribution studies are now carried out for most extreme weather events around the world. As just one example, it has been estimated that climate change increased the rainfall from Hurricane Harvey by about 15% (IOP). The American Meteorological Society puts out an annual review of extreme events and their connection to climate change, and they find that most extreme events have been affected by climate change (AMETSOC). Thus, it would be correct to say the data and analysis shows that climate change is already making many extreme weather events more extreme.

### 1.9.5 Impacts on Human Society and Natural Ecosystems

As our climate changes, human systems will respond to these changes; this is discussed in the next section. But many of the impacts of climate change will be on natural

systems that humans do not manage, and those impacts will be much more difficult to mitigate. These natural ecosystems provide enormous benefits to human society. For example, mangrove forests that grow in shallow salt-water coastal regions provide protection for coastal areas from erosion, storm surge (especially during hurricanes), and tsunamis. Pollination by bees is a key part of the growth cycle of many economically beneficial crops (e.g., apples, almonds, blueberries). As the climate shifts and ecosystems are impacted, the benefits provided for free by these ecosystems may disappear, and the resultant costs will be shifted onto society. In China, for example, a decline of wild bees has forced farmers to hire people to go from flower to flower and hand-pollinate the flowers using tiny brushes.

One particular worry for both natural and human systems is that the climate will not warm linearly as greenhouse gases are added to it linearly. Rather, we will add enough greenhouse gas that the climate system will undergo a large and rapid shift to an entirely new climate state – this is colloquially known as a **climate tipping point**. An example of an abrupt change occurred roughly 12,000 years ago, as the Earth was emerging from the depths of the last ice age, when temperatures in the Northern Hemisphere plunged several degrees on a timescale of decades due to a disruption in the ocean currents.

Research on potential abrupt changes has revealed a number of possible places in our climate system where abrupt changes could occur. These include

- another shutdown of the Gulf Stream, similar to that described above, leading to rapid, widespread changes in climate;
- a rapid disintegration of the West Antarctic or Greenland ice sheets, which could raise sea level by several meters in a century or less;
- thawing of permafrost and methane hydrates, which would release huge amounts of greenhouse gases into the atmosphere, leading to additional warming and an acceleration of climate change; and
- a shift in the timing and magnitude of the Indian monsoon, changing seasonal rainfall that billions of people rely on.

It is difficult to assess the probability of a tipping point occurring. Climate models do not reliably predict the

occurrence of an abrupt climate change, and many experts view the probability to be low, although not zero, over the coming century. If an abrupt change did occur, though, it could be a catastrophe for both human and natural systems because the rate of change is so high for these kinds of events. This is why these kinds of events pose such a challenge for risk management.

## POLICY RESPONSES

Our responses to climate change can be broadly split into three categories: adaptation, mitigation, and geoengineering. Adaptation means responding to the negative impacts of climate change. If climate change causes sea level to rise, an adaptive response to this impact would be to build sea-walls or relocate communities away from the encroaching sea. Mitigation refers to policies that avoid or minimize climate change in the first place, thereby preventing impacts such as sea level rise from occurring. This is accomplished by reducing emissions of greenhouse gases, usually through policies that encourage the transition from fossil fuels to energy sources that do not emit greenhouse gases. Geoengineering refers to active manipulation of the climate system. Under this approach, our society could continue adding greenhouse gases to the atmosphere, but we would intentionally change some other aspect of the climate system in order to cancel the warming effects of the greenhouse gases. For example, we could engineer a decrease in the amount of solar energy absorbed by the Earth. If done correctly, this could stabilize the climate despite continuing emissions of greenhouse gases. In the rest of this chapter, we explore each of these options in detail.

### 1.10 Adaptation

Any climate change that is not avoided must be adapted to. And because the climate is presently changing and, even under the most optimistic scenario, will continue to change for decades, adaptation must be part of our response to climate change.

Individuals will adapt without any direction from the government. When the climate changes in agricultural areas, for example, farmers will need to change their farming practices to avoid bankruptcy. For example, they can change

farming practices by switching to drought-resistant plant species, add infrastructure to irrigate their fields more effectively, or take any number of similar actions to adjust to the realities of a new climate.

However, leaving adaptation up the individual has the significant disadvantage that some of the most effective adaptive responses take enormous resources or require large-scale societal coordination. For example, think about the complexities in building a seawall. Effective sea walls cover an entire community and therefore require consensus from that community on whether to make that significant investment, and also how to best make that investment. Because of this, many of the possible adaptive responses require a significant role be played by the government—in both organizing decisions about large-scale infrastructure and in providing resources.

It is also worth noting that one person's adaptation can modify impacts elsewhere. A good example of this is building a levee on a river. While that may reduce flooding around the levee, a reduction in flooding there will push water—and flooding—downstream. This can lead to levee wars in which communities building higher levees force other communities to raise their levees, reducing flood impacts to their area but pushing flooding into other areas.

Another issue with adaptation is that the ability of societies to adapt to climate change varies from place to place. Financially stable and well-governed countries like the United States and transgovernmental organizations like the European Union will be able to adapt far more effectively than less financially stable places with strong public institutions. This creates a tension in the climate debate—the societies most responsible for climate change, who emitted the most carbon dioxide into the atmosphere, are also the richest countries. Because of their wealth, they are also most capable of dealing with the impacts. Those who will be most negatively affected are also the poorest countries, who have contributed the least to the climate problem.

In addition to direct aid, governments can also implement regulations and financial incentives to encourage citizens to adapt to a changing climate. Regulations promoting water conservation, for example, would help communities adapt to decreased freshwater availability caused by climate change. Governments can also reform existing policy that encourage us to be poorly adapted to the present

(or future) climate and that increase our vulnerability to climate change, such as setting the price of flood insurance too low.

Finally, governments can facilitate adaptation by providing reliable information about climate change. Telling people that the parcel of land they're considering building a house on will likely flood in the next few decades may convince them to build elsewhere, saving society the costs of rebuilding the house. The government can also provide technical assistance about possible responses to climate change—that is, helping a farmer figure out what farming practices she needs to change in order to be better adapted to a drier climate.

## 1.11 Mitigation

Mitigation refers to actions that reduce emissions of carbon dioxide and other greenhouse gases, thereby preventing the climate from changing. In our present energy system, most energy comes from combusting fossil fuels. The amount of carbon dioxide produced per unit of energy generated is known as the carbon intensity. The highest carbon intensity fuel is coal, followed by oil, and lastly natural gas. Over the past decade, coal has been replaced in many places with natural gas because of cost and environmental concerns. This trend away from coal is expected to continue in the future.

Solving climate change requires our society replace fossil fuels with climate-safe energy sources that do not release carbon dioxide into the atmosphere. Solar energy is the renewable energy source with the most potential. To satisfy all human energy needs would require roughly 1 million km<sup>2</sup> to be covered with solar energy collectors. This would be equivalent to a square with 1,000 km on each side and corresponds to 0.2% of the Earth's surface. Although this is a large area, it is comparable to the total area covered by cities, so there is no reason to believe that it is impossible for humans to construct this area of solar collectors, distributed around the world.

Wind is another important and prolific climate-safe energy source. A single one of today's electricity-generating wind turbines can generate as much as 10 MW of power. Taking into account the intermittency of wind, we could satisfy humanity's energy requirement with a few million wind turbines. It should be noted that putting up wind turbines does not preclude using the land simultaneously for other

activities, such as agriculture. In addition, wind turbines can be put offshore with an additional benefit that offshore wind typically blows more consistently and intermittency is less of an issue than for land-based wind.

**Wind** and **solar** energy have been growing rapidly over the past decade and are emerging as important contributors to our energy supply. The price of these energy sources has declined rapidly over the years, and they are competitive or even cheaper than conventional fossil-fuel energy in many places. There is no question that this trend will continue and wind and solar will become a bigger part of our energy mix.

The primary problem with wind and solar is intermittency—the Sun shines only during the daytime and when not obscured by clouds, and the wind speed varies with meteorological conditions. But people want energy when they want it, so wind and solar need to be combined with other technologies to ensure that power is always available. In the short-term, natural gas provides the most likely way to cover periods when wind and solar fall short of demand. In the longer run, energy storage technologies will likely become the dominant resource. These technologies include batteries, enhanced transmission of power, so that regions generating wind and solar can send that power to regions that are not generating the power, and dispatchable carbon-safe power, such as geothermal and nuclear.

Biomass energy is another renewable option; it refers to the process of growing plants and then burning them to yield energy. Because the carbon dioxide released from burning biomass was absorbed from the atmosphere during the growth of the plant, there is no net increase in carbon dioxide in the atmosphere. While people have been utilizing biomass energy for nearly all of human existence, there remain important issues with this as a large-scale energy source. For example, global-scale bioenergy source will require enormous amounts of land. This can be problematic because we already farm most productive land, so additional land typically comes from clearing forest, which causes a host of other local environmental impacts, such as loss of native biodiversity and ecosystem degradation. These issues need to be assessed and addressed before we embark on an expansion of this energy source.

Hydroelectric energy is generated when water running through a dam spins turbines and generates electricity. It is the most widespread renewable energy source in the

world today, providing 16% of the world's electricity in 2018 (IEA). Despite the many advantages of this energy source, it seems unlikely that this power source can be greatly expanded. Many of the world's big rivers are already dammed, and new dams often cause local environmental problems that generate significant local political opposition.

One of the most contentious options for reducing greenhouse gas emissions is nuclear energy. Nuclear energy is a mature technology that generated about 10% of the world's electricity in 2018, so there is no question about its technical feasibility (Our World in Data). However, there is significant opposition to new nuclear power due to several factors. The first is the risk of release of nuclear radiation from an accident (such as occurred in Chernobyl and Fukushima) or from intentional release due to terrorism. Another problem is nuclear waste, which is what comes out of the reactor after the nuclear fuel is burned. This waste is extraordinarily radioactive, and it must be safely isolated for tens of thousands of years. If it were released accidentally, or intentionally in a so-called dirty bomb, the resulting harm in both human cost and ecological damage could be massive.

There is also the problem with proliferation. A nuclear bomb requires only a few kilograms of uranium or plutonium. During the nuclear fuel cycle (the mining and enriching of fuel and the storage of waste), there exists the possibility that small amounts of bomb-grade uranium or plutonium could be diverted with the intent of building a nuclear bomb. This could result in a nuclear weapon in the hands of terrorists or rogue nation, which would present a significant security threat to the rest of the world.

Finally and perhaps most importantly, there is the cost. Nuclear power plants are extraordinarily expensive to build and it is very difficult to find financers. This is one of the primary reasons that few new nuclear power plants have been built in the United States in the last few decades. Any plan to increase the amount of nuclear energy will require new reactor designs that are less costly to build.

A final option to generate energy without emitting carbon dioxide to the atmosphere is known as carbon capture and storage, often referred to as carbon sequestration or by its abbreviation, CCS. CCS refers to a process by which fossil fuels are burned in such a way that the carbon dioxide generated is not vented to the atmosphere. Rather, the carbon dioxide is captured and placed in long-term storage.

The most promising place to store the carbon dioxide is to inject it deep underground in depleted oil and gas fields, coal beds that cannot be mined, or deep saline formations. CCS is technically feasible and has been demonstrated to work in preliminary tests. However, it is presently unclear if this approach is economically feasible at the scale necessary to allow fossil-fuel sources to continue to be an important source of energy without the carbon emissions.

Most analyses of our energy system conclude that renewable energy sources of hydroelectric, geothermal, and wind and solar energy will be our primary sources of power when the fossil-fuel era ends. The impact of intermittency of these power sources can be reduced with some combination of enhanced transmission to bring power from regions where renewables are generating power, energy storage (e.g., batteries), and dispatchable climate-safe energy, meaning energy sources that are always available and can pick up the load when intermittent sources decline. Dispatchable climate-safe power includes energy such as natural gas power with CCS. There are also policies to change demand; that is, the price of power can vary throughout the day, thereby shifting demand to times when power is most abundant.

## 1.12 Geoengineering

A final category of solution to the climate change problem is known as geoengineering, which refers to actively manipulating the climate system in order to prevent the climate from changing despite continuing greenhouse gas emissions. Geoengineering efforts can be roughly divided into two categories.

The first category is known as solar radiation management, and these efforts attempt to engineer a reduction in the amount of solar energy absorbed by the Earth. The most frequently discussed way to do this is to inject sulfur into the stratosphere. Once in the stratosphere, this gas reacts with ambient water vapor to form droplets that reflect sunlight back to space, thereby increasing the reflection of incoming solar energy back to space and cooling the planet. This is the same mechanism by which volcanoes cool the planet. Thus, the physics supporting these suggestions is robust, and we have high confidence that if schemes like this were carried out at a sufficiently large scale, the planet would experience cooling.

There are, however, important disadvantages with these approaches. To begin with, such schemes may have serious side effects. We expect, for example, that solar radiation management will change precipitation patterns, potentially causing droughts in some regions or floods in others. In addition, solar radiation management is a governance nightmare, potentially leading to misunderstanding around causes and effects, and subsequently instigating politically destabilizing conflicts.

A second category of geoengineering is known as carbon dioxide removal. This is an effort to implement processes that rapidly remove carbon dioxide from the atmosphere. Planting trees is an example. As the trees grow, they pull carbon dioxide out of the air and sequester it in wood. The problem with trees as a carbon storage device is that they are not permanent. You can plant a forest and, as the trees grow, carbon is indeed pulled out of the atmosphere. But that forest can burn down, thereby releasing all of the carbon back into the atmosphere. Even in the best case, trees typically only live a few centuries.

Another option is to remove carbon dioxide from the air chemically, a process often referred to as direct air capture. This is like CCS (discussed in the last section), but CCS removes carbon dioxide from the exhaust gas of a power plant, whereas air capture removes carbon from the free atmosphere. A related approach is referred to as bioenergy with carbon capture and sequestration, more commonly referred to by its initials, BECCS. In this process, plants are grown, which removes carbon from the atmosphere. The plants are then burned to produce power, and the carbon dioxide produced is captured and sequestered using CCS technology.

There is no technical barrier to carbon dioxide removal schemes, but the scale required is enormous—humans are adding more than 40 billion tonnes of CO<sub>2</sub> into the atmosphere every year. Carbon dioxide removal must be able to remove a significant fraction of this at a price low enough to not cause problems in the economy. No one knows if this can be achieved.

"well below 2°C above pre-industrial levels" while "pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels." As part of the Paris Agreement process, each country has submitted a nationally determined contribution (NDC), a promise of global emissions reductions that the country intends to achieve.

The Biden Administration committed the United States to cutting overall greenhouse gas emissions by 50% below 2005 levels by 2030 and reaching net-zero emissions by 2050. The E.U. has committed to similar reductions—emissions reduced by 55% in 2030 (below 1990 levels), reaching net-zero emissions by 2050. China committed to leveling off its carbon emissions no later than 2030 and reaching net zero by 2060.

While these emissions reduction commitments are significant, they are not likely sufficient to limit warming to 2°C. Rather, commitments under the Paris Agreement put us on track for 2.5–3°C of warming in 2100, with warming continuing into the twenty-second century and beyond (Climate Action Tracker).

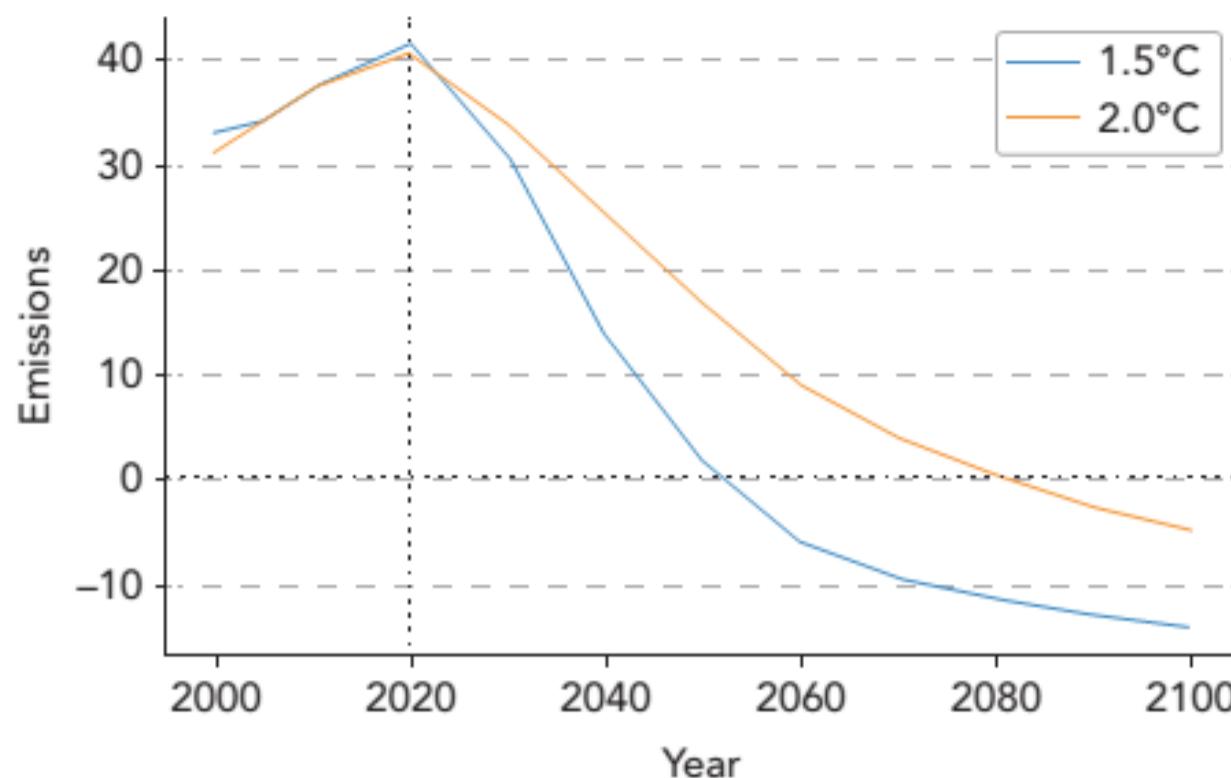
So, what do we have to do to keep warming below 2°C? A useful way to think about this problem is in terms of a carbon budget. It turns out that the peak warming we eventually experience is determined by total cumulative emissions of carbon dioxide since the industrial revolution began around the beginning of the nineteenth century. The scientific community's best estimate is that peak warming is 0.3–0.6°C for every trillion tonnes of carbon dioxide emitted into the atmosphere.

Humans have already emitted about 2.2 trillion tonnes between the industrial revolution and the end of 2017, so we can stay under 2°C warming if we limit future emissions to around 1.5 trillion tonnes. This is a tight budget: With present-day emissions exceeding 40 billion tonnes per year, we will blow through our remaining budget by the 2050s. To stay below 1.5°C is even more daunting. Our emissions budget for that limit is 580 billion tonnes, meaning that we are on track to exceed our budget for stabilizing below this temperature in the 2030s.

Figure 7 shows emissions trajectories consistent with keeping the temperature of the planet below the 2°C and 1.5°C thresholds. Because we have so little carbon budget remaining, emissions need to begin declining immediately. For the 1.5°C threshold, net emissions need to decline to 50% of

## 1.13 Mitigation Targets

The international climate agreement that the world is presently working under, the 2015 Paris Agreement, has the aim of holding the increase in global average temperatures to



**Figure 7** Emissions scenarios for 1.5°C and 2°C.

today's value by the mid-2030s and reach zero in 2050. For the 2°C threshold, net emissions need to decline to 50% of today's value by the mid-2040s and reach zero in 2080.

For both scenarios, emissions continue to decline after they reach net zero and become negative. This means that humans are pulling more carbon dioxide out of the atmosphere than they are releasing using approaches discussed in the geoengineering section above. These negative emissions imply the removal of potentially hundreds of billions of tonnes of carbon dioxide from the atmosphere over a few decades. This is an enormous task, to put it mildly, and our ability to accomplish this is entirely speculative. Nevertheless, it is clear that achieving either temperature target may be unattainable without the ability generate large negative emissions.

There are other trajectories that achieve 1.5°C and 2°C. However, they all have a fundamental trade-off between the speed of emissions reductions right now and negative emissions later this century. If a trajectory reduces emissions more slowly over the next decade or two, then we will need quicker emissions reductions later.

## SUMMARY

This chapter has provided a short introduction to climate science and policy. The scientific community is confident the Earth is warming, and it is extremely likely that humans are the main driver of this warming. It is possible that warming over the coming century will be a few degrees Celsius, an amount comparable to the warming since the last ice age. The exact amount will lead to vastly different outcomes in different places (IPCC).

This warming is already and will continue to bring with it changes in many other aspects of the climate system, including changes in the distribution and intensity of precipitation, increases in sea level, changes in ocean chemistry, and many others. There is also a chance the climate system will experience a tipping point, where the climate suddenly transitions into a new climate regime. These changes will affect many of the things that humans care about, including the human and natural systems that we rely on.

Humans have a range of options in response. We can try to prevent the climate from changing (mitigation), adapt to the changing climate (adaptation), or try to engineer a more hospitable climate (geoengineering). Most of the discussion and conflict over climate policy is over efforts to mitigate climate change, which requires us to transition from fossil fuels to renewable energy.

Under the Paris Agreement, the countries of the world have agreed to a mitigation target of limiting warming to well below 2°C above pre-industrial temperatures, with an aspirational goal of limiting warming to 1.5°C. Achieving this will be challenging and will require emissions reductions to accelerate and reach net-zero sometime in the second half of this century. It will also require negative emissions, where humans pull more carbon dioxide out of the atmosphere than they emit, with much more being required for the 1.5°C target.

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