2025

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Sustainability and Climate Risk

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Sustainability and Climate Risk Exam

Pearson

Pearson Education, Inc., 221 River Street, Hoboken, NJ 07030
A Pearson Education Company
www.pearsoned.com

Printed in the United States of America

00040344-00000001 / A103001322216

EEB/KC

Pearson

ISBN 10: 0-13-538957-7
ISBN 13: 978-0-13-538957-7

Contents

Note: The 2025 SCR Curriculum continues to reference TCFD guidance and case studies as numerous private and public sector entities (as well as other standards) have incorporated TCFD principles into their current reporting and sustainability strategies. Though TCFD has disbanded formally as a monitoring and reporting organization, TCFD-produced resources, technical reports, recommendations, and case studies are considered useful by the ISSB and closely aligned with IFRS reporting. Several governments that began incorporating TCFD principles are currently endorsing or committing to adopting disclosures based on ISSB recommendations. Since organizations and climate risk professionals continue to use TCFD guidance on a variety of topics, the SCR will continue to reference such guidance. GARP will monitor the work of the ISSB and amend the curriculum as necessary going forward.

Chapter 9 will go into more detail about the high-level differences between the two. Please reference https://www.ifrs.org/sustainability/knowledge-hub/making-the-transition-from-tcfd-to-issb/ for FAQs about this transition.

PREFACE

To Our SCR Candidates:

It's been three years since GARP first offered its Sustainability and Climate Risk (SCR) certification pçrogram. In those three years the SCR program has gained global acceptance, becoming the world's leading certificate program addressing sustainability and climate-related risks.

The world's ability to understand and deal with the numerous complex challenges of climate change and the risks it brings has grown. But there are still many areas where we, as individuals, have room to grow and learn.

Each year, new and more-complex issues arise. Each year, with the assistance of the climate experts who are members of our SCR Advisory Committee, we at GARP strive to address in the SCR program newly identified climate-related challenges, and to bring areas of climate risk that are literally just developing to your attention.

The world has made progress in reducing global emissions that affect climate change, and in looking at the physical and transition risks associated with moving to a lower carbon environment. But as is universally acknowledged, there is much more to do.

Even if emissions are effectively lowered to globally agreed-upon objectives, climate change will continue to affect our lives. Among other things, nature-related events such as extreme weather (i.e., heat, drought, wildfires, flooding) will affect living conditions globally, including financial, real economy, and energy firms. They all will have transition and physical risk impacts well into the future.

In recognizing this, we introduced into this year's SCR curriculum two additional areas of climate risk-related coverage: Transition planning and carbon reporting; and the risks associated with natural assets that can be caused by climate change, or what is generally referred to as nature-based climate risk. Understanding and measuring nature-based risks is still in its infancy in terms of data, assessments, and how to make informed decisions in this area. But the need to understand nature-based climate risks and how they differ from global climate risks is imperative.

In addition, and in keeping with the program's dynamic nature, we've also added curriculum updates addressing the current state of climate risk assessment, placed additional focus on assessment tools and methodologies, provided scenario analysis case studies, set out principles and implementation strategies for transition planning, and included an in-depth discussion relating to understanding carbon emissions, carbon accounting, and carbon reporting.

And you will find some excellent explanatory videos surrounding the above subjects. The videos were developed by global experts to make learning with the SCR program practice-based and enjoyable.

Our role with the SCR program is to provide you with the necessary understanding and some tools to allow you to inform others, enhance your decision-making processes, and drive change. This will all lead to informed action in your and your firm's drive to a sustainable, net-zero future.

We hope you enjoy the learning experience that our global experts have developed in this vitally important space. And we wish you the very best in your pursuit of the SCR certificate.

Yours truly,

Richard Apostolik

President & CEO

PREPARING FOR THE 2025 SCR EXAM

Congratulations on your decision to increase your awareness of sustainability and climate risk and join a growing global community of Sustainability & Climate Risk (SCR) certificate holders.

The SCR Exam is practice oriented. Exam questions reflect the theory presented in program materials and true-to-life work experience. Exam candidates must not only understand sustainability and climate-risk concepts, but should be able to apply these concepts in real-life settings. The program curriculum covers skills and knowledge areas necessary to understand today's rapidly evolving climate-risk landscape. The SCR Exam is comprehensive, testing candidates on a number of sought-after sustainability and climate-risk standards and practices.

In an effort to offer optimized learning tools for SCR Exam candidates, GARP created study materials to increase the likelihood of a successful Exam outcome. Access to the following Study Materials is **complimentary** for all candidates registered to take the SCR Exam in 2025:

SCR Study Guide and Learning Objectives. This guide includes a complete list of chapter topics, required online readings, and key learning objectives.

SCR eBook. The official eBook for the SCR Exam includes required readings across the ten chapters of the curriculum. Each chapter begins with a set of learning objectives to guide candidates through key concepts of the chapter.. A Glossary of key terms and an abbreviations list appear at the end of the book. NOTE: The abbreviations list is available for reference during the SCR Exam.

Required Online Readings. In addition to information contained in the 2025 SCR book, the SCR Exam covers a selection of online material from leading academics and practitioners. These online readings are a required part of the SCR curriculum and may be reflected in the SCR Exam questions.

SCR Practice Exam. This 90-question multiple-choice exam includes sample questions similar to questions covered on the SCR Exam. These questions broadly reflect material assigned for 2025and represent a multiple-choice question style the SCR Advisory Committee considers appropriate. Question style includes stand-alone questions and questions aligned with case studies. Explanations are included for correct and incorrect answer choices.

SCR Curriculum Errata. If candidates identify a potential error or discrepancy in the curriculum, they may contact GARP directly. GARP reviews all errata submissions received and posts updated errata, including appropriate corrections. Visit the GARP website regularly for the latest SCR Curriculum errata summary.

GARP Learning Platform. The platform is accessible via the candidate portal on any device—mobile, tablet, or desktop computer. Through the platform, candidates can monitor their study performance and determine strengths and weaknesses. Candidates can access the SCR curriculum and create their own study plans through flashcards, end-of-chapter questions, and the full-length Practice Exam. Our new optional SCR Climate PAL provides additional practical applied learning opportunities to enhance the study experience. SCR Climate PAL is not covered on the Exam.

These Study Materials are available at https://www.garp.org/scr/study-materials.

Best of luck in your study preparation. We appreciate your support of the SCR Program.

Regards,

Beth Gould Creller
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Foundations of Climate Change: What Is Climate Change?

Learning Objectives

After completing this reading you should be able to:

- Define climate change and differentiate between weather and climate.
- Identify the evidence used to support modern climate change trends.
- Describe the Earth's climate history and different methods for measuring non-anthropogenic climate change.
- Understand how the Earth's energy balance and the greenhouse effect affect the climate.
- Know the primary greenhouse gases and aerosols, their sources, and relative contribution to climate change.
- Explain non-human and human mechanisms that contribute to climate change.
- Understand the distribution, frequency, and intensity of climate driven environmental impacts across geography and time.
- Understand the distribution, frequency, and intensity of climate driven socioeconomic impacts across geography and time.
- Explain the different approaches and key considerations of climate change adaptation, including maladaptation.
- Identify and discuss the opportunities, strategies, technologies, and associated challenges of mitigating climate change.
- Understand the opportunities and drawbacks of implementing geoengineering techniques to combat climate change.
- Explain carbon budgets, national commitments, and emissions scenarios to limit temperature increases.

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.

Chapter Outline

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 tell someone that the average daily high temperature for your city in August is 84°F/29°C, that's climate.

A simple analogy to explain the difference between weather and climate involves tossing a six-sided die. Today'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 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 or more.

Climate change describes the long-term differences in the statistics of weather 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 four of the six 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.

OBSERVATIONS OF CLIMATE CHANGE

1.1 Modern Climate Change

While we have a greater number of high-quality weather observations in the last several decades, 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 1.1a 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 1.3°C over this time (calculated as the difference between the 1850–1900 average and the 2014–2023 average). As of early 2024, the warmest year in the record was 2023 followed by 2016, 2020, 2019, 2017, and 2022. Overall, the ten hottest years in the record are the last ten years (2014–2023).

Figure 1.2 shows how the warming in Figure 1.1a 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

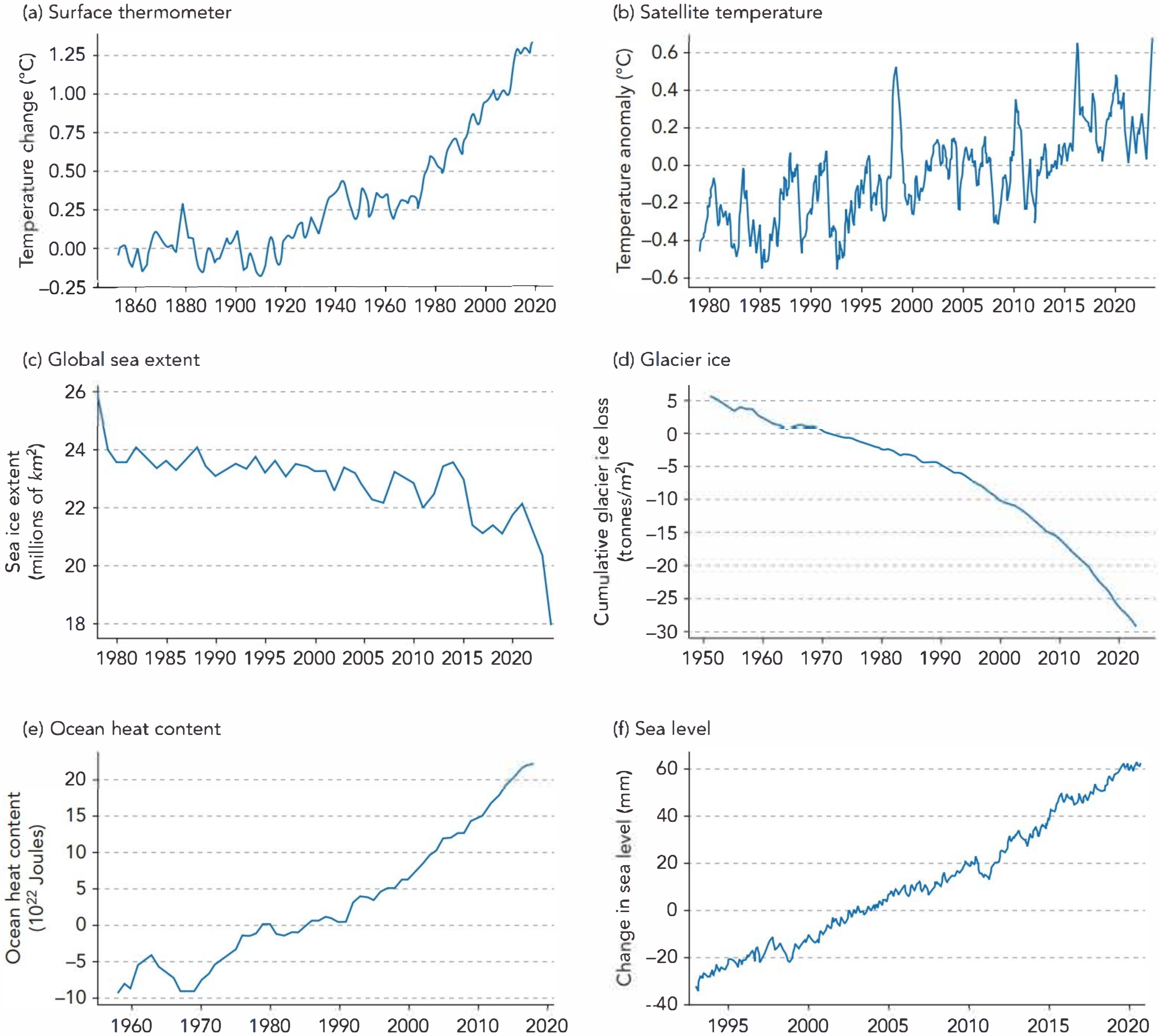

Figure 1.1 **(a) Global annual average temperature (°C), relative to the 1850–1900 average. (b) Satellite measurements of the global monthly average temperature anomaly (°C), relative to the 1991–2020 period. (c) Arctic sea-ice extent (in millions of square kilometers) in September of each year. (d) Global average cumulative mass change of the world's glaciers, tonnes/m^2. (e) Ocean energy content (Joules) of the top 2000 m of the world ocean, relative to the 1979–1994 mean. (f) Global-average sea level change, measured by satellite-borne instruments, in millimeters. The seasonal cycle has been removed.**

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 1.1a.

The data in Figures 1.1a and 1.2 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, and yet there have not been any legitimate issues in the data or analyses found.

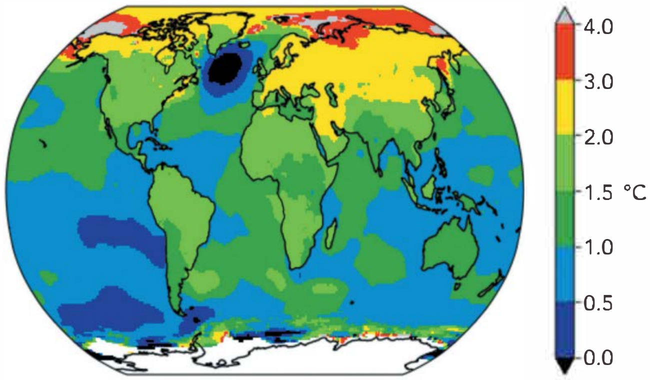

Figure 1.2 **The distribution of modern warming (in °C). Warming is calculated as the difference between the 1850–1900 average and the 2014–2023 average.**

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 1.1b) agrees well with the trend in the surface temperature record (Figure 1.1a). We can also look at indirect evidence of warming, that is, the effects that warming would cause our planet to experience. Figures 1.1c and 1.1d show that ice on the planet is disappearing—something we would expect in a warming climate.

Over 90% 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. Figure 1.1e 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 1.1f shows that sea level is rising. There are two key contributing factors to the rise in sea level. One contributor is the melting of grounded ice (melting of floating ice does not raise sea level). When it melts and the water runs into the ocean, the total amount of water in the ocean increases and sea level rises. Figure 1.1d shows that we are losing grounded ice on the planet, and we expect that to drive an increase in sea level. Second, water expands when it warms. Figure 1.1e confirms that the oceans are 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.

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. Trees can live for centuries, and by combining the record from modern trees with trees that were cut down centuries ago and, for example, used in timber of old buildings, we can extend the tree-ring record to give us climate information going back about a millennium.

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 (e.g., stalactites and stalagmites): 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.

These data show that the Earth has experienced large climate fluctuations over its history. Figure 1.3a 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 little permanent ice on the planet. Since then, the climate has generally been cooling.

Figure 1.3b shows the last 410,000 years, and it shows that the planet has been cycling between cold periods, known as ice ages, and warmer periods, known as interglacials. 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 pleasant interglacial period.

Figure 1.3c 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

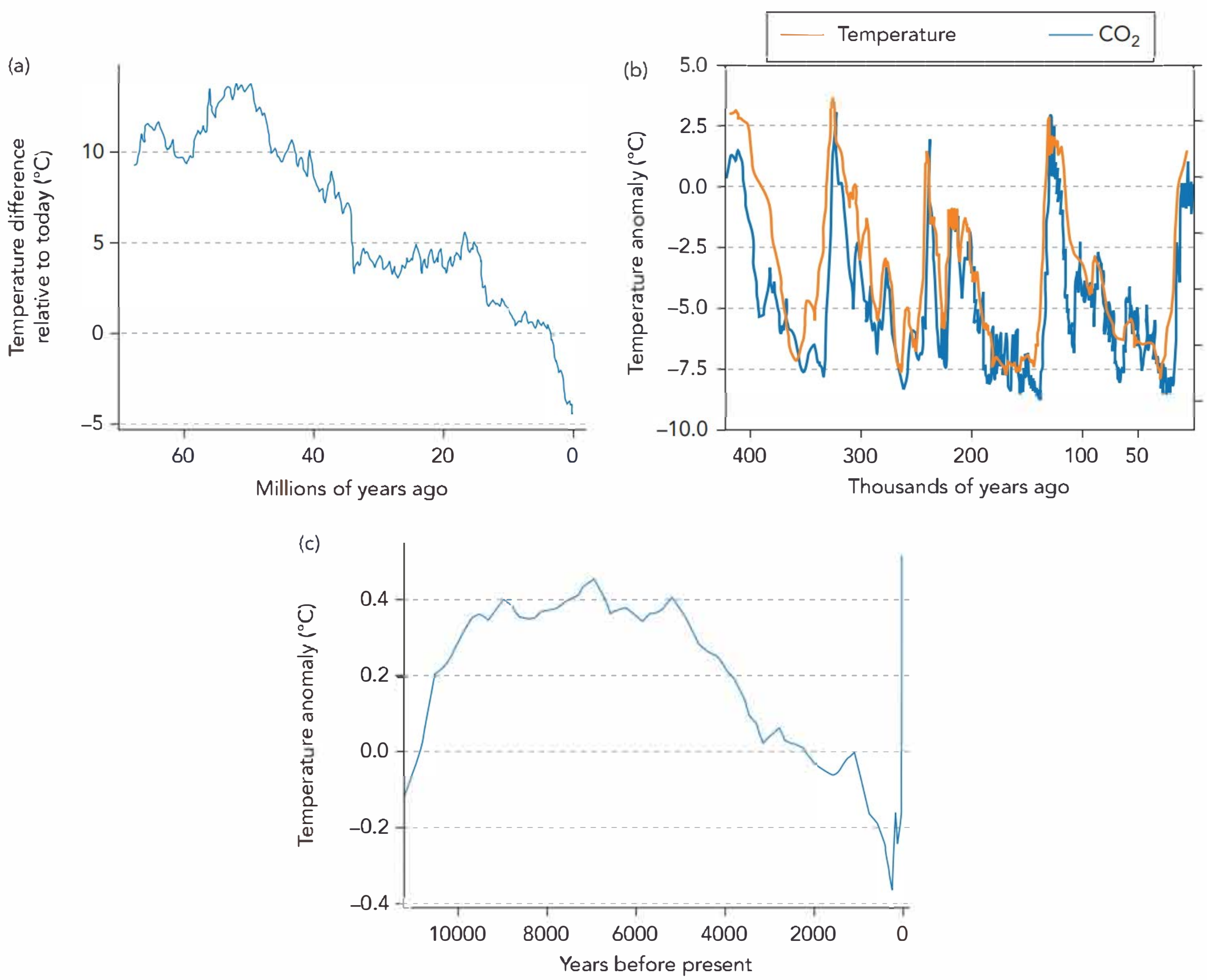

Figure 1.3 **(a) Reconstructed global average surface temperature over the past 70 million years, relative to today's temperature. (b) Temperature of the southern polar region (solid line) over the past 410,000 years, relative to today's temperature, constructed from an Antarctic ice core. Carbon dioxide (dotted line) is from air bubbles trapped in the ice. (c) Global temperature of the last 11,000 years, relative to the 1961–1990 average, based on multiple proxy records.**

200 to 300 years ago, known as the Little Ice Age. After that, the Earth began warming, and in the early 2020s, it was about 1.2°C warmer than the Little Ice Age and 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 1.2°C warming the Earth has experienced since the nineteenth century is not an insignificant amount of warming—it is 20% of the warming that transitioned us out of the last ice age. In addition, human society, made up of mega-cities and trillions of dollars of infrastructure on a global scale, has only been around since the industrial revolution (around 1800) and, since that time, society has experienced a small range of global temperatures. 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).

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 W/m^2 of energy to the Earth (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 Earth is 238 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 radiant 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. Therefore, 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 energy 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.

Merely having an atmosphere does not produce a greenhouse effect; the atmosphere needs to have the right composition to absorb infrared radiation. The majority of Earth's 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. The amount of water vapor in the atmosphere is highly variable, ranging from a few percent in warm tropical marine regions to a fraction of a percent in cold polar regions. Carbon dioxide's strong contribution occurs despite the fact that it made up only 0.042% of our atmosphere in 2023. This is an awkwardly small number, so the concentration is usually written as 420 parts per million (ppm), meaning that, in every million molecules of air, about 420 molecules are CO_2.

1.5 How Humans Are Changing the Climate

The previous section showed that 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

The possibility that human emissions of carbon dioxide from fossil fuel combustion could warm the climate was hypothesized 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.

But it wasn't until the mid-twentieth century that direct measurements of the abundance of carbon dioxide in the atmosphere showed it was increasing. The measurements are plotted in Figure 1.4, 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 multiple lines of evidence. First, 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). Of the 56% that is removed, about half is absorbed into the ocean and leads to ocean acidification, which we will discuss later in this chapter. The other half is absorbed by the land biosphere through enhanced plant growth.

The fact that the increase in atmospheric carbon dioxide each year is (on average) slightly less than half of what humans 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.

Second, the chemical composition of atmospheric carbon dioxide also shows that the increase in Figure 1.4 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 1700s, before the industrial revolution, there was about 280 ppm in the atmosphere. By the early 2020s, humans have increased atmospheric carbon dioxide by about 50%.

1.5.2 Other Greenhouse Gases and Aerosols

The next most important greenhouse gas is methane (CH_4), which has increased from 0.8 ppm before the industrial revolution to above 1.9 ppm in 2020. This might seem like a small increase, particularly compared to the 140-ppm increase in carbon dioxide, but methane is a far more powerful greenhouse gas—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 28x 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 (N_2O) 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 1.1), so that even small increases can trap a significant amount of heat in our climate system.

Finally, there is ozone (O_3), a molecule with multiple effects on the atmosphere. It is well known for its ability to absorb ultraviolet radiation, which is harmful to human health and natural ecosystems. However, ozone is also a greenhouse gas that contributes to trapping heat in the atmosphere. While humans do not directly emit ozone into the atmosphere, they do emit

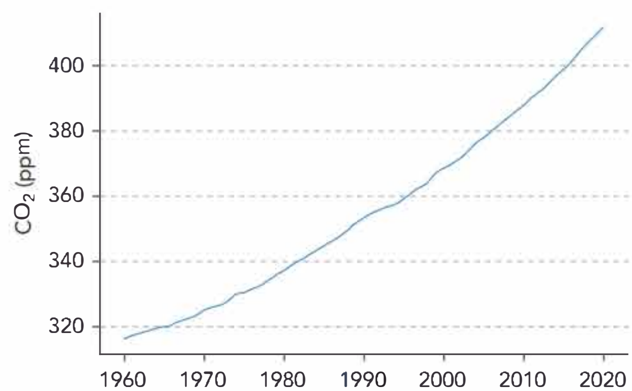

Figure 1.4 The record of annual average atmospheric carbon dioxide since the middle of the twentieth century.

Table 1.1 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

Species	Atmospheric Lifetime	Global Warming Potential (GWP)	Increase in Abundance Since Pre-Industrial	Fraction of Total Greenhouse Radiative Forcing
Carbon dioxide	500 years	1	140 ppm	56%
Methane	11.8 years	28	1.1 ppm	15%
Nitrous Oxide	109 years	273	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.

the precursors that lead to the formation of ozone, such as hydrocarbons and nitrogen oxides. Over the past few decades, the increase in these precursors has led to an increase in ozone in the lower atmosphere, which contributes to the trapping of heat. It is important to distinguish this type of ozone from the ozone found in the stratosphere. In the 1970s and 1980s, it was discovered that humans were destroying ozone in the stratosphere, but this is a different phenomenon from the increase in lower atmospheric ozone that is warming the climate.

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

Humans generate aerosols through a range of processes. For example, 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 United States), and industrial practices (e.g., cement production).

As a result of human activities like this over the past two centuries, the abundance of aerosols has increased, and this has generated a cooling effect that partially offsets the warming effect of the increase in greenhouse gases. The exact percentage of this offset is uncertain and varies depending on the source and type of aerosols, and many other factors. However, aerosols are also primary components of air pollution, which kills millions of people every year, so countries are making strong efforts to reduce their abundance. As that happens, the offsetting effect of these aerosols declines and global warming will accelerate.

1.5.3 Summarizing Human Impact on The 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, whereas aerosols have caused a negative (cooling) change to radiative forcing. The net human contribution, including several other small forcings, is positive, which is illustrated in Figure 1.5.

You might be wondering why water vapor does not appear in Figure 1.5, 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

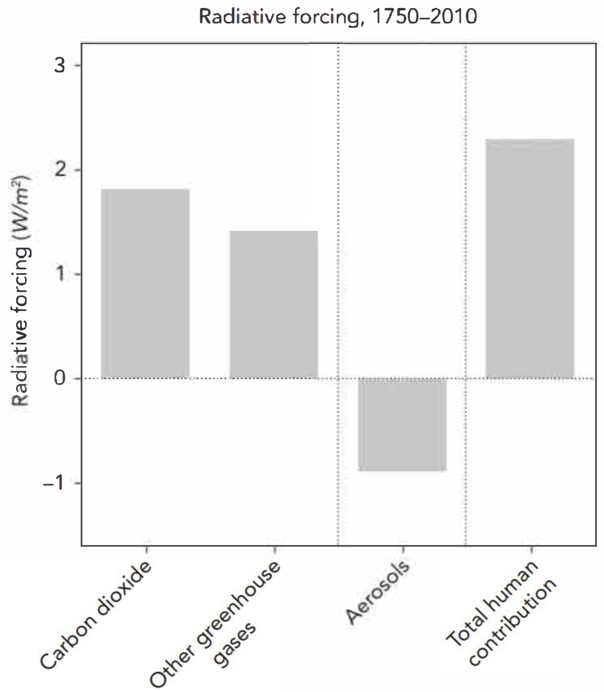

Figure 1.5 **Radiative forcing caused by changes in the climate between 1750 and 2019.**

water vapor in the atmosphere decreases. Emissions of water vapor directly from human activities contribute essentially nothing to its atmospheric abundance.

Because water vapor's abundance in the atmosphere is set by the temperature, water vapor's main role in climate change is to amplify changes caused by things like increasing 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 (Dessler, 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 incoming 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, e.g. 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°, cycles from 22.3° to 24.5° 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 1.3b) 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 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 observed warming since the industrial revolution, nor observations supporting unforced variability as causing this observed warming. 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 1.3b) 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 Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change, published in 2021, came to the following conclusion:

> It is unequivocal that human influence has warmed the atmosphere, ocean, and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred.

In other words, it is beyond doubt that humans are warming the climate system. However, that statement does not tell you how large this human influence is. Thus, the report follows up by saying:

The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C.

Since the observed warming over that period was about 1.1°C, this means that the best estimate is that humans are responsible for 100% of the observed warming of the climate system. Note the use of the word *likely* here. The IPCC uses a set of carefully defined terms to express confidence. In the parlance of the IPCC, *likely* denotes a confidence of 66%. Said another way, the IPCC is 66% confident that all observed warming is human caused.

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 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 each represents a different way the world may evolve in the future. It is worth noting that the numbers 1–5 in the name of each scenario indicate a continuum of potential climate outcomes, with SSP1 representing the most optimistic and SSPs 3, 4, and 5 the most pessimistic. Furthermore, SSP4 is rarely used in the climate literature, and we will not consider it further in this chapter.

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 1.6a), which leads to different amounts of carbon dioxide emitted into the atmosphere each year (Figure 1.6b). Given these emissions scenarios, the resulting atmospheric concentrations of carbon dioxide can be calculated (Figure 1.6c) 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 1.6d).

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

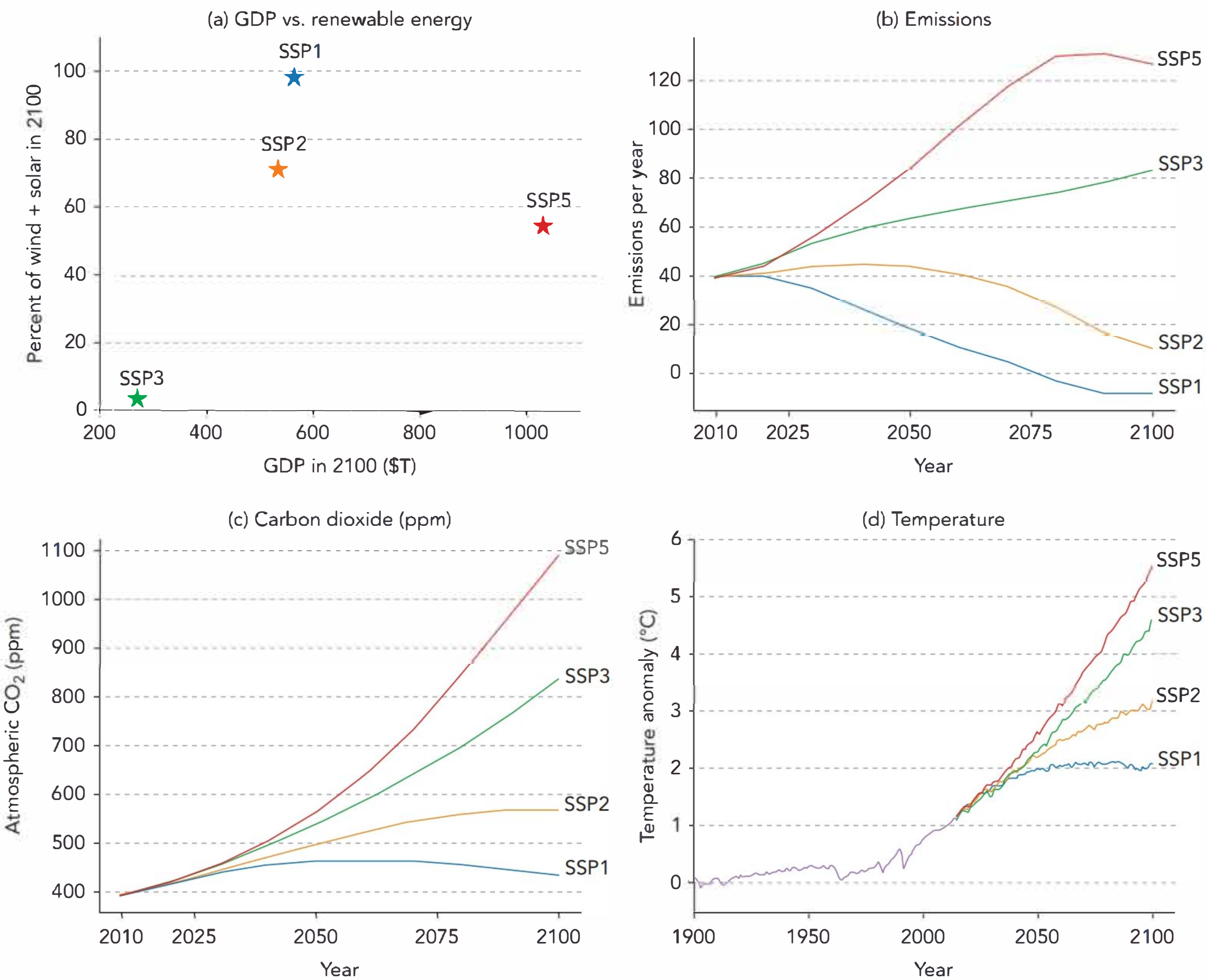

Figure 1.6 **(a) GDP in 2100 (trillions of 2005 US dollars) versus the sum of wind and solar capacity as a% of total (final) energy consumption in 2100.**

(b) Emissions of carbon dioxide (billions of tonnes of carbon dioxide per year).

(c) Atmospheric carbon dioxide (ppm).

(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.

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 at the opposite end from 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 and technological advancements, some of which have not yet been made. However, at present, it seems that the SSP2 emissions scenario is the one we are on track to most closely follow. Obviously, the future is not yet certain and the decisions we make in the next decade or two could radically alter our climate trajectory and which SSP scenario turns out most accurate. Because many people alive today might live well into the second half of the century, the resulting climate impacts would affect us, not just future generations.

While the SSPs are the most commonly used scenarios today, you may still see references to an earlier set of scenarios, known as the Representative Concentration Pathways, abbreviated RCPs. As their name suggests, these are a set of concentration pathways, but without corresponding economic drivers. The more advanced SSPs were designed to span the same range of future climates as the RCPs and for each RCP scenario, there is a roughly similar SSP scenario (this is discussed in Chapter 7).

1.9 Impacts of Modern Climate Change

A few degrees of global-average warming over the next century would have significant impacts to life on Earth. Although local temperatures can vary considerably over time, the global average temperature of the Earth is very stable, with random variations of just a few tenths of a degree per year. Moreover, seemingly small changes in global average temperature, like those in the different SSP scenarios, 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/10°F 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 these changes was a completely different distribution of ecosystems.

Thus, warming of a few degrees Celsius over the coming century (Figure 1.6d), would be comparable to the warming since the last ice age and implies enormous changes in our environment. This would be challenging 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 some 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 there are also negative effects of warmer winters, such as less wintertime insect mortality, leading to increased agricultural damage from pests, or less wintertime precipitation falling as snow, reducing snowpack and meltwater, stressing freshwater supplies during the spring and summer, and increasing the frequency and intensity of wildland fires.

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, the warming will not be uniform across the globe. In a continuation of the observed patterns seen in

Figure 1.2, we expect continents to warm more than oceans and to have more warming in the northern hemisphere than in the southern hemisphere. 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 1.6d.

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 work outside. 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. Higher temperatures also require people to run the air conditioners more, and this costs money.

1.9.2 Precipitation

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, 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 increase the occurrence of flood events. The increase in the fraction of heavy events also increases the average 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 and therefore changing the form of precipitation will change the timing of runoff. This will increase the availability of water in winter and spring and decrease it in summer. Places that rely on a particular timing of runoff, such as how the U.S. Pacific Northwest relies on summertime runoff during their dry summers, will be impacted. Impacts would include reduced freshwater and hydroelectric power availability as well as reduced recreational opportunities.

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 costly new infrastructure to protect against flood events in some regions and droughts in others. It may also be politically destabilizing as it exacerbates political tensions over access to water.

1.9.3 Sea Level Rise & 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 1.1f) 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 Sixth Assessment Report (AR6) contains predictions that sea level will rise 44 to 76 cm (17 to 30 inches) above today's levels by 2100 under the most likely emissions scenario (SSP2). Even though such a sea level rise 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 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 melting is a secondary effect after temperature rises, the impacts of ice melting take longer to realize. 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 (e.g., corals, mollusks, crustaceans) 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 acidity will increase to the point where it is fatal for these species.

1.9.4 The Albedo Effect, Polar Amplification, and Positive Feedbacks

Similar to the "water vapor feedback" process discussed in section 1.5.3, a decline in sea and land ice can amplify warming beyond the release of GHGs. Ice is more reflective—it has a higher albedo—than the darker ocean or land. Thus, previously ice-covered areas absorb more solar radiation, heating up the atmosphere, which in turn, melts more ice, exposing more dark areas and reducing the Earth's overall albedo—the albedo effect.

Water vapor feedback, polar amplification, and any other self-reinforcing warming phenomena are "positive feedbacks." A feedback loop either speeds up or slows down a change in a system. As discussed, a positive feedback accelerates a change, in this case, warming. A negative feedback—such as a condition in which cloud cover accelerated, increasing albedo—would slow down warming. However, negative feedback loops play less of a significant role in modern climate change than positive feedback loops. Feedback loops can also play an important role in climate tipping points, discussed below.

1.9.5 Extreme Events

While we've previously been focused on average conditions, many 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 always have a natural "weather" component that climate change amplifies. For example, extreme heat waves occur when climate change is added on top of an otherwise ordinary heat wave. Similarly, extreme sea level events occur when ordinary storm surge from coastal storms adds to sea level rise due to climate change.

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 technique uses statistical analysis of historical climate data. 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 was just a statistical fluke.

Thus, the second technique focuses on our understanding of the physics of the phenomenon. In a warmer world it should be obvious why 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 tornado outbreaks are affected by global warming.

Finally, we use computer simulations (i.e., GCMs) of the climate to evaluate frequency and intensity of extreme events. 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 characteristics of the observed event rarely or never occurs in the simulated world without climate change, but does in a world with simulated 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% (Van Oldenburgh et al., 2017). 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.

1.9.6 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 societally and economically beneficial crops (e.g., apples, almonds, blueberries). As the climate shifts and ecosystems are impacted, the benefits provided 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 some farmers to hire people to go from flower to flower and hand-pollinate the flowers using tiny brushes.

One concern 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 in a few decades due to a disruption in the ocean currents.

Research on potential abrupt changes has revealed several possible places in our climate system where abrupt changes could occur. These include:

- similar to that described above, another shutdown of the Gulf Stream that leads to rapid, widespread changes in regional 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 of any particular tipping point to be low over the coming century. There are enough possible tripping points, however, that even if the probability of individual tipping points is low, the chance of at least one of them tipping is decidedly non-negligible. If an abrupt change did occur, 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 seawalls 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, primarily 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. 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. Adaptation is primarily a response to physical climate risk, which will be detailed in subsequent chapters.

Adaptation actions can physically manifest in human-built infrastructure or enhancement of ecosystem services and functions, such as protection of mangrove forests to quell storm surges or expanding forested areas to improve water quality. Beyond physical enhancements, human communication, processes, regulations, and so forth can be adaptive, such as better extreme event warning systems or more climate-informed zoning regulations. Individuals can adapt without any direction from the government, if they have sufficient resources. For example, when the climate changes in agricultural areas, farmers will change their farming practices to avoid bankruptcy. 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 to 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, consider 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 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. This requirement for significant resources has profound implications for equity and justice of adaptation. Because not everyone has those resources, policies that rely extensively on adaptation policies run the risk of exacerbating existing inequalities.

It is also worth noting that one person's adaptation can change 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.

The previous example shows how an action that decreases climate vulnerability for one community can increase exposure to risk for another. This is maladaptation, an intended adaptation action that actually increases climate vulnerability. Maladaptations can increase vulnerability immediately or sometime in the future. The negative effects of maladaptations can include not just an increase in vulnerability but also an increase of greenhouse gases or an imposition of disproportional burdens on the most vulnerable populations.

Insurance policies can lead to maladaptation. Home or building insurance policies, a seemingly adaptive risk management practice, can lead to building in areas at increasing risk from climate impacts because the builder believes that, if a climate impact occurs, they are covered. Building sea walls or other coastal defense structures can sometimes lead to increased erosion and damage to neighboring areas, thus creating new vulnerabilities and negatively impacting ecosystems. Planting trees is often seen as a way to address climate change but planting non-native or monoculture tree species can have unintended consequences such as reduced biodiversity, increased vulnerability to pests and diseases, and potential disruptions to local water cycles.

Another issue with adaptation is that the ability of societies to adapt to climate change varies. Financially stable and well-governed countries like the United States and transgovernmental organizations like the European Union will be able to adapt more effectively than less financially stable places without strong public institutions. This creates a tension in the climate debate—the societies most responsible for climate change, who historically 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 (maladaptation) to climate change, such as setting the price of flood insurance too low (as happens in the United States).

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 has a higher likelihood of flooding 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.

1.11.1 Emissions from the Current Energy System

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. Of the most commonly used fossil fuels, coal has the highest intensity, followed by oil, and lastly natural gas (see Table 1.2).

GHGs can be measured in grams or kilograms per million British thermal unit (MMBtu) and organizations typically report total emissions in metric tons (tonnes). There are 1,000 kilograms in

Table 1.2 Carbon intensity of various fuels. GHGs can be measured in grams or kilograms per million British thermal unit (MMBtu) and organizations typically report total emissions in metric tons. Methane (CH_4) and Nitrous Oxides (N_2O) are measured in smaller amounts, grams. However, due to their higher Global Warming Potential, small emissions of these GHGs can have significant impact

Fuel[1]	kg CO_2/MMBtu	g CH_4/MMBtu	g N_2O/MMBtu
Coal	100[2]	11	1.6
Motor gasoline	70	3	0.60
Propane	63	3	0.60
Natural gas	53	1	0.10

[1] Taken from US EPA Emission Hub https://www.epa.gov/system/files/documents/2022-04/ghg_emission_factors_hub.pdf; https://www.epa.gov/climateleadership/ghg-emission-factors-hub

[2] Depending on type of coal (e.g., anthracite, bituminous), CO_2 emissions factors can range from 93 — 103 kg CO_2/MMBtu

a tonne. So, an organization that used 30,000 MMBtus of propane in a year would report 1,890 tonnes CO_2 = 30,000 MMBtus × (63 kg CO_2/MMBtu ÷ 1,000 kg/tonne).

Beyond accurately reporting organizational GHG emissions, understanding carbon intensities/emissions factors plays an important role in energy policy discussions. Because of its relatively lower carbon intensity, natural gas has been heralded as a cleaner fossil fuel than coal and "coal-to-gas switching" as a "bridge" to help countries transition to more clean-energy. However, methane leakage, the escape of methane during extraction or transport of natural gas, has called into question the value of natural gas in this transition.

1.11.2 Moving Toward a Cleaner Energy System

Ultimately, stabilizing the climate means getting emissions down to zero. This requires our society to replace fossil fuels with climate-safe energy sources that do not release carbon dioxide and other greenhouse gases into the atmosphere. Solar energy is the renewable energy source with the most potential generation capacity. To satisfy all human energy needs would require roughly 1 million km^2 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 panels, distributed around the world.

Wind is another important climate-safe energy source. Today's electricity-generating wind turbines typically generate 5–10 MW of power. Considering 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 blows more consistently, so intermittency is less of an issue than for land-based wind although comes with additional technical challenges to get that power to customers.

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 issue 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 power when they want it, so a grid containing a significant amount of wind and solar must be balanced with dispatchable carbon-safe energy sources. Dispatchable sources are always available and can be modulated to counteract the intermittency of wind and solar. **Hydroelectric** power is generated when water running through a dam spins turbines and generates electricity. It is the most widespread dispatchable 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 and social problems that generate significant local political opposition.

Another significant source of climate safe and dispatchable energy 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). Nuclear power plants are expensive to build, and 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. Opposition to new nuclear power plants also arises because of the environmental risks of that power. One particularly frightening risk is of release of nuclear radiation from an accident (such as occurred in Chernobyl and Fukushima) or from intentional release due to terrorism.

Another potentially important source of dispatchable power is **geothermal**, in which water, pumped underground, heated by the Earth, and brought back to the surface, is used to turn a turbine and generate power. While frequently used in places with active volcanism, like Iceland, companies are working on producing low-temperature geothermal, which can be used much more widely. This technology uses drilling techniques pioneered by the natural gas industry, so it's a key area for fossil fuel companies and their workforce to transition to the green economy.

Other sources of dispatchable power are more problematic. **Biomass** energy 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, a 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.

A final option to generate dispatchable power without emitting carbon dioxide to the atmosphere is known as *carbon capture, utilization, and storage*, often shortened to carbon capture, carbon sequestration, or by its abbreviation, CCUS. CCUS 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 used in a range of applications, such as being incorporated in cement or plastic.

The carbon can also be stored. 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. Such storage is technically feasible and has been demonstrated to work in preliminary tests. Overall, it is presently unclear if CCUS 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.

Battery energy storage systems (BESS) may also play a role in two ways. Short-term storage (a few hours) can be used to shift energy produced at the peak of solar power, around local noon, to the peak of demand, in the late afternoon/early evening. This would play a key role in smoothing out the intermittency of solar energy. The cost of batteries is coming down quickly and such short-term storage is already a component of some grids, such as in California. Longer-term storage (days to weeks) would potentially displace the need for dispatchable power. At this point, however, long-term storage at sufficient scale is not feasible. Research on new technologies now occurring means that this may become possible in the future.

Batteries require elements like cobalt, which come from politically volatile regions like central Africa. In some cases, the mining is done for low pay and in dangerous conditions, making ethical issues in the supply chain prominent, just as they are with fossil fuels. Recently, Chinese mining companies have moved aggressively to gain control of strategically important mines, potentially adding political uncertainty. Clearly, the supply chain is a risk for future production of batteries. However, as the use of batteries increases, this risk will be mitigated by an expanding battery-recycling industry.

Ultimately, to reach a zero-emission economy, as many economic activities as possible must be electrified. This will greatly increase consumption of electricity compared to a scenario where we continue to rely on fossil fuels. That in turn will require enhancements in infrastructure, such as enhanced transmission lines. An enhanced transmission system would also help reduce the impact of intermittency of solar and wind energy by allowing the transfer of energy from regions with excess renewable energy to regions where demand exceeds supply.

Some important economic processes may be difficult to electrify, including international airline flights and long-distance trucking. For these, biofuels or hydrogen energy might play a role due to their large energy per unit mass. The fuel must be produced in a way that does not produce greenhouse gases, such as producing hydrogen from electrolysis of water powered by renewable energy. Hydrogen could also be used in place of batteries for storage—it could be produced when there is excess renewable power and then converted back to electricity when more power is needed. A downside of hydrogen is that it is difficult to store, and it carries a significant explosion risk, as evidenced by the Hindenburg accident. This means that any widespread adoption of hydrogen would require significant investment in new hydrogen infrastructure.

The clean-energy transition must be carefully managed. A reliable and climate-safe energy system will contain a mix of power sources: wind and solar will produce a lot of power, but it also must contain dispatchable power that will pick up the load when wind and solar are not able to generate sufficient energy. One of the biggest risks is that our existing fossil fuel energy sources are shut down too soon, before climate-safe energy sources are able to provide the 24-hour-per-day reliable power that everyone expects. Maintaining reliable power may require keeping open economically non-competitive fossil fuel plants until the grid can be robustly maintained by climate-safe energy.

The transition must also be managed in a way that ensures that it is economically and politically feasible. This includes ensuring that the transition is equitable and that access to clean energy is available to all, regardless of income level or location.

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 three 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 disputes over 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 CCUS (discussed in section 1.11.2), but CCUS 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.

A final category is what are referred to as **natural climate solutions**. These are practices and technologies that can help sequester carbon from the atmosphere and reduce emissions, thereby reducing the impacts of climate change. These solutions often involve the conservation, restoration, and management of natural systems, such as forests, grasslands, and wetlands, which can absorb and store carbon dioxide. To the extent that they eliminate emissions, there is some ambiguity about whether these belong in mitigation or geoengineering. Some examples of natural climate solutions include:

1. Forest conservation and reforestation: Forests absorb and store carbon dioxide from the atmosphere through the process of photosynthesis. Protecting existing forests and planting new trees can help sequester carbon and reduce emissions from deforestation and land use change.
2. Agroforestry: This involves the integration of trees into agricultural landscapes, which can aid in sequestering carbon.
3. Wetland restoration: Wetlands, such as marshes and swamps, are important carbon sinks because they store carbon in the soil and vegetation. Restoring wetlands can help increase their capacity to sequester carbon and provide other ecosystem benefits, such as improving water quality and flood control.
4. Grassland restoration and management: Grasslands, such as prairies and savannas, can also absorb and store carbon. Restoring and managing grasslands in a way that promotes carbon sequestration, such as using cover crops

and reduced tillage, can help reduce greenhouse gas emissions.

5. Soil carbon sequestration: Soil contains a large amount of carbon, and certain practices, such as conservation tillage, cover cropping, and the use of organic fertilizers, can help increase the amount of carbon stored in the soil. This can help reduce emissions from the agriculture sector and improve soil health.

There are minimal technical barriers to carbon dioxide removal schemes, but the scale required is enormous—humans are adding more than 40 billion tonnes of CO_2 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 disrupt the economy. No one knows if this can be achieved.

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 "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. In support of this, the US government has passed two laws that support climate action: 2021's Infrastructure Investment and Jobs Act and 2022's Inflation Reduction Act. The Inflation Reduction Act is the more significant legislation, investing USD 319 billion in provisions related to climate and clean energy. These investments take the form of direct spending on infrastructure like electric vehicle charging, loan guarantees for innovative clean energy programs, and incentives and tax breaks for clean energy projects. There are also provisions to incentivize the domestic manufacture of clean energy components and critical minerals.

The E.U. has committed to similar reductions—in 2030, emissions should be 55% below 1990-level emissions, 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 in and of themselves, they are not 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.

From the beginning of the industrial revolution up until the present day, humans have already emitted more than 2 trillion tonnes of carbon dioxide. But we can stay under 2°C warming goal if we limit future emissions to around 1.2 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 250 billion tonnes, meaning that we are on track to exceed our budget for stabilizing below 1.5°C in the 2030s.

Figure 1.7 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 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

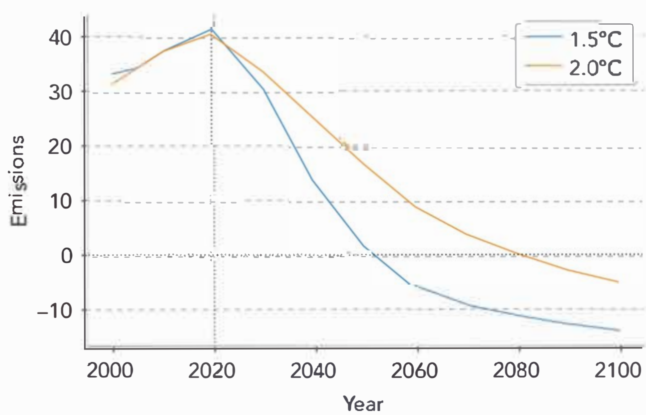

Figure 1.7 **Emissions scenarios for 1.5°C and 2°C.**

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, achieving either temperature target may be unattainable without the ability to generate large negative emissions.

There are other trajectories that achieve 1.5°C and 2°C. They all feature 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 larger negative emissions later.

SUMMARY

This chapter has provided a short introduction to climate science and policy. The scientific community is confident the Earth is warming, and 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. According to the IPCC, the exact amount will lead to vastly different outcomes in different places.

This warming is already and will continue to bring 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 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 likely require negative emissions, where humans pull more carbon dioxide out of the atmosphere than they emit, with much more necessary for the 1.5°C target.

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2

Sustainability

Learning Objectives

After reviewing this chapter, you should be able to:

- Define the three different aspects of sustainability.
- Explain how different entities use Environmental Social Governance (ESG), corporate responsibility, and sustainable development criteria to implement and report sustainability and climate practices.
- Explain the relationship and intersection among sustainability, ESG, and/or climate change.
- Describe the key features of the United Nations (UN) Sustainable Development Goals (SDGs) and Millennium Development Goals (MDGs).
- Discuss strategies for implementing and aligning with the SDGs and how SDG alignment can be material to companies.
- Define ecosystem services, subcomponents, and natural capital. Understand how organizations depend upon and can impact ecosystem services.
- Trace the evolution of sustainability in governments, corporations, and financial institutions.
- Know the different types of greenwashing. Describe how organizations can "greenwash" and "greenwish" sustainability claims and the actions to counteract these practices.
- Describe the life-cycle assessment (LCA) process and how organizations use this tool to advance sustainability.
- Understand sustainability reporting frameworks and initiatives, their objectives, and to whom they are targeted.