

— THIRD EDITION —

INTRODUCTION TO MODERN CLIMATE CHANGE

ANDREW E. DESSLER

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Introduction to Modern Climate Change

Third Edition

The third edition of this introductory textbook for both science students and non-science majors has been brought completely up to date. It reflects the most recent findings from the latest Intergovernmental Panel on Climate Change (IPCC) reports, as well as advances in the political arena around climate change. As in previous editions, it is tightly focused on anthropogenic climate change. The first part of the book concentrates on the science of modern climate change, including evidence that the Earth is warming and a basic description of climate physics. Concepts such as radiative forcing, climate feedbacks, and the carbon cycle are discussed and explained using basic physics and algebra. The second half of the book goes beyond the science to focus on the economics and policy options to address climate change. The book's goal is for a student to leave the class ready to engage in the public policy debate on the climate crisis.

Andrew E. Dessler is a climate scientist and professor of atmospheric sciences at Texas A&M University. He researches atmospheric chemistry, climate change, and climate change policy. He is a fellow of the American Geophysical Union and the American Association for the Advancement of Science. The first edition of this book won the Louis J. Battan Author's Award from the American Meteorological Society. He has authored two books on climate change: this one, and *The Science and Politics of Global Climate Change: A Guide to the Debate* (with Edward Parson, third edition 2019, Cambridge University Press).

“Andrew Dessler is that rare breed of scientist who can contribute at the leading edge of scientific discovery while adeptly explaining the science and its implications to lay audiences. With his newly revised edition of *Introduction to Modern Climate Change*, Dessler provides a comprehensive, up-to-date, and engaging account of the science, the impacts, and the policy dimensions of the climate crisis. Climate change is the defining challenge of our time and this textbook is the ideal choice to ensure students are informed about it.” Michael Mann, Penn State University, author of *The New Climate War and Dire Predictions*

“In a world dominated by headlines, Dr. Andrew Dessler’s *Introduction to Modern Climate Change* delivers a fresh take on something we’re all craving: fundamentals. The book begins with the physical science basis for climate change, from blackbody radiation to the fluxes and reservoirs of the carbon cycle, before delving into hot topics, from feedbacks to exponential growth. Dessler delivers a robust and much-needed framework for addressing modern global environmental change.” Hari Mix, Santa Clara University

“*Introduction to Modern Climate Change* has been my text of choice for a general education class on the topic. It provides students with the foundations of climate physics, places modern variations in the context of the geologic record, establishes the man-made nature of current trends, and (uniquely for textbooks on this matter) discusses the economic and political dimensions of the problem, and how best to respond to it. This new edition brings a significant upgrade by adding the most up-to-date numbers from the IPCC and the Paris Agreements, as well as a greatly expanded set of engaging graphics, conveying the information most pertinent to this existential crisis. I heartily recommend this approachable textbook to any student or scholar.” Julien Emile-Geay, University of Southern California

“*Introduction to Modern Climate Change* is essential reading for anyone interested in anthropogenic global warming. Andrew Dessler’s textbook is easily accessible for students from a range of backgrounds, as no prior knowledge of Earth Science is needed. It is the first resource I add to my reading lists, and the new color figures enhance it further. There are also important updates concerning the policies of climate change, such as the impact of the Trump Administration and the Paris Agreement.” Matt Smith, University of Worcester

“ . . . an excellent textbook for the general audience of undergraduates . . . In the third edition, there are more exercises than in earlier editions, allowing the instructor to emphasize those exercises depending on the particular department providing the course . . . An important update is the transition to colored graphics throughout the book, which bring to life the arguments in the text . . . Dessler is a very gifted writer for the general reader . . . In this book, he engages the reader with relevant analogies from everyday life . . . Most importantly, his presentation is clear. His arguments are strong and presented passionately . . . I grade the third edition as *excellent*.” Gerald R. North, Texas A&M University

From reviews of previous editions:

“... a textbook about the scientific basis for global climate change that's well balanced, well written, highly illuminating, and accessible to non-science majors.” John M. Wallace, University of Washington

“I was so impressed with its simple and compelling coverage of the science of climate change, and, just as importantly, its social and political context. The students loved the book – some even commented that it was the first time they had actually understood and enjoyed reading a science book.” Steve Easterbrook, University of Toronto

“Dessler’s book is written so clearly that anyone can read it and understand the major issues in climate change. It hits just the right balance between rigor and comfort, making the whole topic more appealing and accessible to students.” Deborah Lawrence, University of Virginia

“The text provides a readable, concise summary of the science of climate change, but it is the non-scientific aspects of the book that set it apart ... a well-crafted textbook. The writing is very accessible without being too simplistic. The combination of a broad overview of the science and the policy of climate change is both novel and appropriate for ... an introductory-level survey course on climate change. Reading the book was a learning experience for me, and I would happily recommend this book to anyone seeking an introduction to climate change.” Guillaume Mauger, *Bulletin of the American Meteorological Society*

“The book reads extremely well: it uses stories, analogs, and examples to draw the reader into the story of the science of our changing planet. Despite the complexity of the actual science, Dessler presents the material in a clear manner and does it without drawing on mathematics any more difficult than simple algebra ... I recommend this book for anyone interested in learning more about climate change and the challenges it presents to humanity.” Donald J. Wuebbles, *Physics Today*

“Dessler has done an excellent job of clearly describing the different issues of climate change in a way that will be accessible to both science and non-science majors. I can see this book becoming the standard textbook for the growing number of introductory courses that discuss both the science and policy of climate change.” Darryn Waugh, Johns Hopkins University

“Dessler does an excellent job of simply explaining the science ... should be on the reading list of anyone with an interest in climate science, if for no other reason than that it introduces a complex subject in such a coherent and comprehensible fashion.” John Brittan, *The Leading Edge*

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THIRD EDITION

Andrew E. Dessler

Texas A&M University



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Preface

Future generations may well view climate change as the defining issue of our time. The worst-case climate change scenarios look truly terrible, but even middle-of-the-road ones portend unprecedented environmental change for human society. When looking back on our time and the choices we made (or didn't) to save our planet, young people will either cheer our foresight in dealing with this issue or curse our lack of it.

I want to stress that this isn't an advocacy book. Although I have opinions on this matter, and strong ones, I also believe that in this case facts speak louder than one's beliefs. Thus, in this textbook I limit myself to presenting the science of climate change and laying out the possible solutions and trade-offs among them. The hope is that an unbiased assessment of this issue will prove to people that climate change poses a serious risk to us all, and that reducing our emissions of greenhouse gases will head off that risk.

I recognize that, despite the stakes, the world has done close to nothing to avert the terrible outcomes presented by the scientists if we don't act now. Why, you might wonder? For one, we mostly respond to immediate threats, and climate change isn't happening fast enough to trigger real panic. Surely, we know that it will pose a threat to future generations; however, acting now would be quite onerous, on so many levels, and what reassurance do we have that re-designing our entire energy sector (or even the entire economy) to reduce carbon emissions won't cause havoc even before climate change will? In such a situation, it is easier to do nothing and wait for disaster to strike – which is why dams are frequently built after the flood, not before.

Nevertheless, every year that our society does nothing to address climate change makes solving the problem both harder and more expensive. Despite all this, I remain optimistic because problems often appear intractable at first. In the 1980s, as evidence mounted that industrial chemicals were depleting the atmospheric ozone layer, it was not at all clear that we could avoid this issue at a reasonable cost. The chemicals causing the ozone loss, namely chlorofluorocarbons, played an important role in our everyday life – in refrigeration, air-conditioning, and many industrial processes – just like fossil fuels, the main cause of modern climate change, play an important role in our society. Yet the cleverness of humans prevailed, leading to the development of a substitute chemical, which seamlessly and cheaply replaced the ozone-destroying halocarbons, at a cost so low that hardly anyone noticed when the substitution took place.

Solving the climate change problem will be harder than solving the ozone depletion problem – how much harder, no one knows. I am confident, though, that the ingenuity and creativeness of humans is such that we can succeed without damaging our standard of living. That said, there is only one way to find out, and that is to try to do it.

Key Features

- While discussing all facets of climate change, this book focuses on how human activities have directly contributed to this problem.
- It describes the physics of climate change, allowing students to fully appreciate the science behind this phenomenon and the deep concern shared by the scientific community for the future of our planet.
- It also addresses its many other dimensions – science, economics, society, and politics as well as the moral and ethical questions posed by this problem. Indeed, virtually every government in the world has now accepted the reality of climate change, and the debate has, to a great extent, moved on to policy questions, including the economic and ethical repercussions that this has on our society.

Updates Since the Previous Edition

- New and revised figures.
- Includes the latest development and research findings on climate change, from “attribution science” and its central role in informing discussions of responsibility for climate change to Earth’s climate sensitivity and its significantly narrowed bounds.
- Discusses the policy of climate change, the recent (anti-) environmental policy changes in countries such as the United States, and international negotiations and agreements such as the Paris Agreement.
- Identifies the synergies and trade-offs between climate change mitigation and adaptation policies.

Book Organization

The first seven chapters of the book focus on the science of climate change. Chapter 1 defines the problem and provides definitions of weather, climate, and climate change. It also addresses an issue that most textbooks do not have to address: why the reader should believe this book as opposed to websites and other sources that give a completely different view of the climate problem. Chapter 2 explains the evidence that the Earth is warming. The evidence is so overwhelming that there is little argument anymore over this point, and my goal is for readers to come away from the chapter understanding this.

Chapter 3 covers the basic physics of electromagnetic radiation necessary to understand the climate. I use familiar examples in this chapter, such as the incandescent light bulb, to help the reader understand these important concepts. In Chapter 4, a simple energy-balance climate model is derived. It is shown how this simple model successfully explains the Earth’s climate as well as the climates of Mercury, Venus, and Mars. Chapter 5 covers the carbon cycle. Feedbacks, radiative forcing, and climate sensitivity are all discussed in Chapter 6.

Finally, Chapter 7 explains why scientists are so confident that humans are to blame for the recent warming that the Earth has experienced.

Chapter 8 begins an inexorable shift from physics to non-science issues. It discusses emissions scenarios and the social factors that control them, as well as what these scenarios mean for our climate over the next century. Chapter 9 covers the impacts of these changes on humans and on the world in which we live. Chapter 10 covers exponential mathematics. Exponential growth is a key factor in almost all fields of science, as well as in real life. In this chapter, I cover the math of exponential growth and explain the concepts of exponential discounting and the social cost of carbon.

Starting with Chapter 11, the discussion is entirely on the policy aspects of the problem. Chapter 11 discusses the four classes of responses to climate change, namely adaptation, mitigation, solar radiation management, and carbon dioxide removal, and their advantages, disadvantages, and trade-offs. The most contentious arguments over climate change policy are over mitigation, and Chapter 12 discusses in detail the two main policies advanced to reduce emissions: carbon taxes and cap-and-trade systems.

Chapter 13 provides a brief history of climate science and a history of the political debate over this issue, including discussions of the United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement. Finally, Chapter 14 pulls the last three chapters together by discussing how to decide which of our options we should adopt, particularly given the pervasive uncertainty in the problem.

Overall, it should be possible to cover each chapter in 3 hours of lecture. This makes it feasible to cover the entire book in one 14-week semester. At Texas A&M, the material in this book is being used in a one-semester class for non-science majors that satisfies the university's science distribution requirement. Thus, it is appropriate for undergraduates with any academic background and at any point in their college career.

Readership and Pedagogy

Any serious understanding of climate change must be quantitative. Therefore, the book assumes a knowledge of simple algebra. No higher math is required, nor prior knowledge of any field of science – just an open mind and a willingness to learn.

To help students in their learning journey, each chapter includes: both quantitative and qualitative questions to test their knowledge of the topics discussed; chapter summaries outlining the major points of the chapter; and a list of important terms to familiarize themselves with and utilize in their discussion about climate change.

Online Resources

Downloadable figures from the book, solutions to selected exercises and a test bank for instructors are available from www.cambridge.org/dessler3. For additional reading and lecture videos, please link up to my website www.andrewdessler.com.

Acknowledgments

This book could not have been written without the incredible work of the climate science community. Ignored by many, demonized by some, I believe that future generations will look back and say, “They nailed it.” I hope this book does justice to all of our hard work. The first edition of the book was written while I was on faculty development leave from Texas A&M University during fall 2010. I thank the university for this support.

1

An Introduction to the Climate Problem

In this chapter, we begin our tour through the climate problem by defining weather, climate, and climate change. We also discuss something that few textbooks address: why you should believe this book.

1.1 What Is Climate?

The American Meteorological Society defines *climate* as

The slowly varying aspects of the atmosphere–hydrosphere–land surface system. It is typically characterized in terms of suitable averages of the climate system over periods of a month or more, taking into consideration the variability in time of these averaged quantities.¹

Weather, on the other hand, is defined as

The state of the atmosphere . . . As distinguished from climate, weather consists of the short-term (minutes to days) variations in the atmosphere.²

Mark Twain, in contrast, famously summed it up a bit more concisely:

Climate is what you expect; weather is what you get.

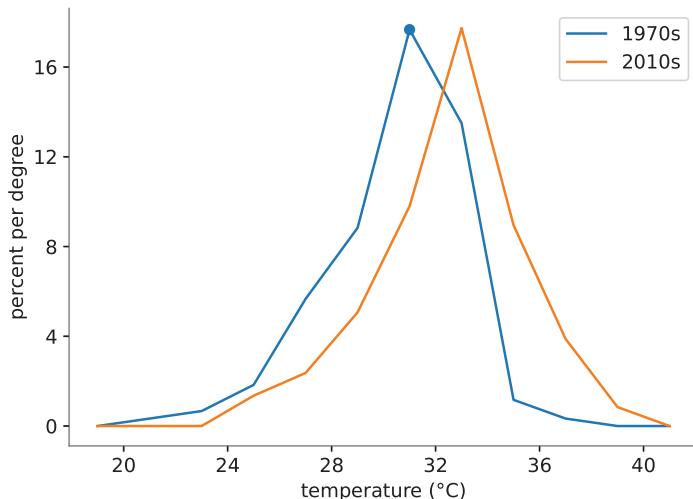
Put another way, you can think of weather as the actual state of the atmosphere at a particular time. Weather is what we mean when we say that, at 10:53 AM on November 15, 2014, the temperature in College Station, Texas, was 8°C, the humidity was 66 percent, winds were out of the southeast at 8 knots, the barometric pressure was 1,023 millibar, and there was no precipitation. Weather is also what we mean when we say that the temperature will be dropping this weekend when a cold front comes through the area.

Climate, in contrast, is a statistical description of the weather over a period of time, usually a few decades. This description would most frequently include quantities such as temperature, humidity, precipitation, cloudiness, visibility, and wind. Figure 1.1 demonstrates one example of a climate statistic: It shows the distribution of daily maximum temperatures in September at Ellington Field, southeast of Houston. During the 1970s, for example, the most likely daily maximum temperature was 31°C, which occurred on

¹ <https://glossary.ametsoc.org/wiki/Climate>, retrieved June 03, 2020.

² <https://glossary.ametsoc.org/wiki/Weather>, retrieved November 25, 2020.

Figure 1.1 Frequency of occurrence of daily high temperature in September at Ellington Field, near Houston, TX, for two time periods: 1970–1979 (blue) and 2010–2019 (orange). HadISD [v3.1.1.2020f] data were obtained from www.metoffice.gov.uk/hadobs/hadisd on 2020-06-03 and are British Crown Copyright, Met Office [7 January 2021], provided under an Open Government Licence, [www.nationalarchives.gov.uk/doc/non-commercial-government-licence/non commercial-government-licence.htm](http://www.nationalarchives.gov.uk/doc/non-commercial-government-licence/non-commercial-government-licence.htm). This data set is described by Dunn (2019), Dunn et al. (2012, 2014, 2016), and Smith et al. (2011).



approximately 18 percent of the days (this point is indicated by the blue dot in the figure). In the 2010s, the most likely maximum temperature was 33°C, which also occurred on 18 percent of the days. The important thing about Figure 1.1 is that it tells us only the range of probable conditions over these two periods. It contains no information about what the actual high temperature was on any day – i.e., you cannot use Figure 1.1 to determine what the actual maximum temperature was on August 10, 1975.

In this book, I frequently use the Celsius scale, the standard temperature scale throughout most of the world (the Fahrenheit scale familiar to US readers is only used in the United States and a few other countries). For readers who may not be conversant in Celsius, you can convert from Fahrenheit to Celsius using the equation $C = (F - 32) \times 5/9$; or from Celsius to Fahrenheit, $F = C \times 9/5 + 32$. It is also useful to remember that the freezing and boiling temperatures for water on the Celsius scale are 0°C and 100°C, respectively. On the Fahrenheit scale, these temperatures are 32°F and 212°F. Room temperature is about 22°C, which corresponds to 72°F.

Why do we care about weather and climate? Weather is important for making short-term decisions. For example, should you take an umbrella when you leave the house tomorrow? To answer this question, you do not care at all about the statistics of precipitation for the month, but rather whether it is going to rain *tomorrow*. If you are going skiing this weekend, you care about whether new snow will fall before you arrive at the ski lodge and what the weather will be while you are there. You do not care how much snow the lodge gets on average or what the average weather is for this time of year.

Climate is important for long-term decisions. If you are looking to build a vacation home, you are interested in finding a place that frequently has pleasant weather – you are not particularly concerned about the weather on any specific day. Plots like Figure 1.1 can help

make these kinds of climate-related decisions; the plot tells us, for example, that a house in this location needs air-conditioning during the summer. If you are building a ski resort, you want to place it in a location that, on average, gets enough snow to generate acceptable ski conditions in most years. You do not care if snow is going to fall on a particular weekend, or even what the total snowfall will be for a particular year.

An example of the importance of both the climate and the weather can be found in the planning for D-Day, the invasion of the European mainland by the Allies during World War II. The invasion required Allied troops to be transported onto the beaches of Normandy, along with enough equipment that they could establish and hold a beachhead. As part of this plan, Allied paratroopers were to be dropped into the French countryside the night before the beach landing in order to capture strategic towns and bridges near the landing zone, thus hindering an Axis counterattack.

There were important weather requirements for the invasion. The nighttime paratrooper drop demanded a cloudless night as well as a full moon so that the paratroopers would be able to land safely and on target, and then achieve their objectives – all before dawn. The sky had to remain clear during the next day so that air support could see targets on the ground. For tanks and other heavy equipment to be brought onshore called for firm, dry ground, so there could be no heavy rains just prior to the invasion. Furthermore, the winds could not be too strong because high winds generate big waves that create problems for both the paratroopers and the small landing craft that would ferry infantry to the beaches.

Given these and other requirements, analysts studied the *climate* of the candidate landing zones to find those beaches where the required weather conditions occurred most frequently. The beaches of Normandy were ultimately selected in part because of its favorable climate, although tactical considerations obviously also played a key role.

Once the landing location had been selected, the exact date of the invasion had to be chosen. For this, it would not be the climate that mattered but rather the *weather* on a particular day. Operational factors such as the phase of the tide and the moon provided a window of three days for a possible invasion: June 5, 6, and 7, 1944. June 5 was initially chosen, but on June 4, as ships began to head out to sea, bad weather set in at Normandy, and General Dwight D. Eisenhower made the decision to delay the invasion. On the morning of June 5, chief meteorologist J. M. Stagg forecasted a break in the weather, and Eisenhower decided to proceed. Within hours, an armada of ships set sail for Normandy. That night, hundreds of aircraft carrying tens of thousands of paratroopers roared overhead to the Normandy landing zones.

The invasion began just after midnight on June 6, 1944, when British paratroopers seized a bridge over the Caen Canal. At dawn, 3,500 landing craft hit the beaches. Stagg's forecast was accurate and the weather was good, and despite ferocious casualties, the invasion succeeded in placing an Allied army on the European mainland. This was a pivotal battle of World War II, marking a turning point in the war. Viewed in this light, Stagg's forecast may have been one of the most important in history.

Temperature is the parameter most often associated with climate, and it is something that directly affects the well-being of the Earth's inhabitants. The statistic that most frequently gets discussed is average temperature, but temperature extremes also matter. For example, it is heat waves – prolonged periods of excessively hot weather – rather than normal high temperatures that kill people. In fact, heat-related mortality is the leading cause of weather-related death in the United States, killing many more people than cold temperatures do. And the numbers can be staggering: In August 2003, a severe heat wave in Europe lasting several weeks killed tens of thousands.

Precipitation rivals temperature in its importance to humans, because human life without fresh water is impossible. As a result, precipitation is almost always included in any definition of climate. Total annual precipitation is obviously an important part of the climate of a region. However, the distribution of this rainfall throughout the year also matters. Imagine, for example, two regions that get the same total amount of rainfall each year. One region gets the rain evenly distributed throughout the year, whereas the other region gets all of the rain in 1 month, followed by 11 rain-free months. The environment of these two regions would be completely different. Where the rain falls continuously throughout the year, we would expect a green, lush environment. Where there are long rain-free periods, in contrast, we expect something that looks more like a desert.

Other aspects of precipitation, such as its form (rain versus snow), are also important. In the US Pacific Northwest, for example, snow accumulates in the mountains during the winter and then melts during the following summer, thereby providing fresh water to the environment during the rain-free summers. If warming causes wintertime precipitation to fall as rain rather than snow, then it will run off immediately and not be available during the following summer. This could lead to water shortages during the summer.

As these examples show, climate includes many environmental parameters. What part of the climate matters will vary from person to person, depending on how each relies on the climate. The farmer, the ski resort owner, the resident of Seattle, and Dwight D. Eisenhower are all interested in different meteorological variables, and thus may care about different aspects of the climate. But make no mistake: We all rely on the stability of our climate for our continuing existence. I will discuss this in greater depth when I explore the impacts of climate change in Chapter 9.

1.2 What Is Climate Change?

The climate change that is most familiar is the seasonal cycle: the progression of seasons from summer to fall to winter to spring and back to summer, during which most non-tropical locations experience significant climate variations. The concern in the climate

change debate – and in this book – is with long-term climate change. The American Meteorological Society defines the term *climate change* as:

Any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer.³

In other words, we can compare the statistics of the weather for one period against those for another period, and if the statistics have changed, then we can say that the climate has changed.

Thus, we are interested in whether today's climate is different from the climate of a century ago, and we are worried that the climate at the end of the twenty-first century will be quite different from that of today. To illustrate this, we return to Figure 1.1 to examine how the distribution of daily maximum September temperatures near Houston, TX changed between the 1970s and 2010s. Clearly, the temperature distributions in these two periods are different – the temperature distribution in the 2010s is about 1.5°C warmer than in the 1970s. We also see that temperatures that rarely occurred in the 1970s occurred frequently in the 2010s. In the 1970s, for example, daily maximum temperatures above 34°C (93°F) occurred on only 3 percent of the days; in the 2010s, they occurred on 35 percent of days. In other words, *the climate of this region changed* between these decades. This plot doesn't tell us what caused the change – it may be due to human activities or any number of natural physical processes. All we have identified here is a shift in the climate.

The shift in the average daily maximum temperature in Figure 1.1 is only 1.5°C , and it may be tempting to dismiss this as unimportant. In Chapter 9, you'll see how small-seeming changes in temperature are associated with significant impacts on the environment and all of us who live in it. So you should not dismiss such a change lightly.

In Chapter 2, we will look at global data to determine if the climate of the entire planet is changing. Before we get to that, however, there are two things I need to cover. First, in the next section, I discuss the coordinate system I will be using in this book.

1.3 A Coordinate System for the Earth

I will be talking a lot in this book about the Earth, so it makes sense to define the terminology used to identify particular locations and regions on the Earth.

To begin, the *Equator* is the line on the Earth's surface that is halfway between the North and South Poles, and it divides the Earth into a northern hemisphere and a southern hemisphere. The *latitude* of a particular location is the distance in the north–south direction between the location and the Equator, measured in degrees (as indicated by the red arrow in Figure 1.2a). This means that the latitude of the Equator is 0° . Latitudes for points in the northern hemisphere have the letter N appended to them, with S appended to points in the southern hemisphere. Thus, 30°N means a point on the Earth that is 30° north of the Equator, whereas 30°S means the same distance south of the Equator.

³ http://glossary.ametsoc.org/wiki/Climate_change, retrieved June 3, 2020.

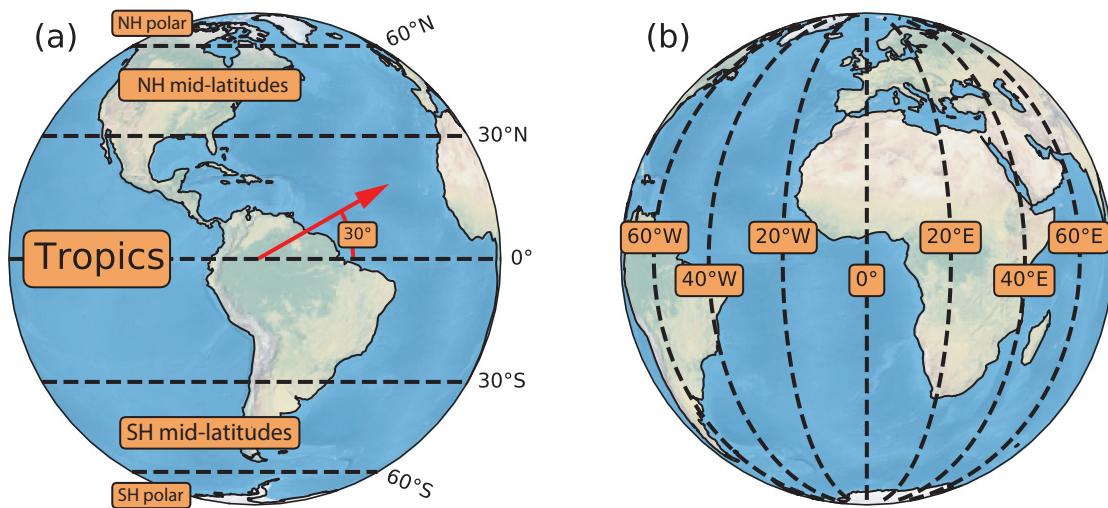


Figure 1.2 (a) A schematic plot of latitude showing the tropics (30°N to 30°S), the northern hemisphere (NH) and southern hemisphere (SH) mid-latitudes (30°–60° in each hemisphere), and the polar regions (poleward of 60° in each hemisphere). (b) A schematic plot of longitude.

The *tropics* are conventionally defined as the region from 30°N to 30°S, and this region covers half the surface area of the planet. The *mid-latitudes* are usually defined as the region from 30° to 60° in both hemispheres, and they occupy roughly one-third of the surface area of the planet. Most human population lives in the northern hemisphere, between the Equator and 60°N, because that's where most of the land is; the southern hemisphere is mainly ocean. The *polar regions* are typically defined to be from 60° to the pole, and together these regions occupy the remaining one-sixth of the surface area of the planet. The North and South Poles are located at 90°N and 90°S, respectively.

Latitude gives the north–south location of an object, but to uniquely identify a spot on the Earth, you need to know the east–west location as well. That is where *longitude* comes in (Figure 1.2b). Longitude is the angle in the east or west direction, from the prime meridian, a line that runs from the North Pole to the South Pole through Greenwich, England, which is arbitrarily defined to be 0° longitude. Locations to the east of the prime meridian are in the eastern hemisphere and have the angle appended with the letter E, whereas locations to the west are in the western hemisphere and have the letter W appended. In both directions, longitude increases to 180°, where east meets west at the international date line.

Together, latitude and longitude identify the location of every point on the planet Earth. For example, my office in the Department of Atmospheric Sciences of Texas A&M University is located at 30.6178°N, 96.3364°W (but please don't show up without an appointment). Knowing your location can literally be a matter of life and death – shipwrecks, wars, and other miscellaneous forms of death and disaster have occurred because people did not know where they were. Luckily for us, GPS (global positioning system) technology, which is built into your cell phone, can determine your latitude and longitude to within a few feet.

1.4 Why You Should Believe This Textbook

I now have to address an issue that generally does not come up in college textbooks: why you should believe it. Students in most classes accept without question that the textbook is correct. After all, the author is probably an authority on the subject, the publisher has almost certainly reviewed the material for accuracy, and the instructor of the class, someone with knowledge of the field, selected that textbook. Given those facts, it seems reasonable to simply assume that the information in the textbook is correct.

But climate change is not like every other subject. If you do a quick Internet search, you can find a website that disputes almost every claim made in this textbook. Your friends and family may not believe that climate change is a serious problem. They may even believe it is a hoax. You may agree with them. This book will challenge many of these so-called skeptical viewpoints, and you may face the dilemma of whom to believe.

This situation brings up an important question: How do you determine whether to believe a scientific claim? This is not just a philosophical question but one of great importance to you. When the coronavirus pandemic hit in early 2020, questions of science (how is it transmitted, do masks protect me, how many people around me are infected?) were literally matters of life and death. In fact, many important policy questions we face are built upon scientific claims.

For climate change, the case for action is built on scientific claims that the Earth is warming, humans are to blame for this, and future warming will bring with it risks of significant impacts. If you happen to know a lot about an issue, you can reach your own conclusions about the scientific claims relevant to that issue. But no one can be an expert on every subject; for the majority of issues on which you are not an expert, you need a shortcut.

One type of shortcut is to rely on your firsthand experience about how the world works. Claims that fit with your own experience are easier to accept than those that run counter to it. People do this sort of evaluation all the time, usually subconsciously. Consider, for example, a claim that the Earth's climate is not changing. In your lifetime, climate has changed very little, so this seems like a plausible claim. However, a geologist who knows that dramatic climate shifts are responsible for the wide variety of rock and fossil deposits found on Earth might regard the idea of a stable climate as ludicrous, and in turn might therefore be less likely to accept a human origin for climate change. The problem with relying on firsthand experience about the climate is that your experience might not be relevant to our present situation. For climate change, that is the case. Our present situation is unique – people have never changed the composition of the global atmosphere as much or as fast as is currently occurring. Thus, whatever the response will be, it will be outside the realm of our and the Earth's experiences.

Another type of shortcut is to rely on your values: You can accept claims that fit with your overall worldview while rejecting the claims that do not. For example, consider the scientific claim that secondhand smoke has negative health consequences. If you are a believer in unfettered freedom, you might choose to simply reject this claim out of hand because its truth implies that governments should regulate smoking in public places to

protect public health. If, on the other hand, you are skeptical about corporate power, you may uncritically accept any claim that implies corporations are engaged in behavior that is bad for consumers.

Yet another shortcut is to rely on an *opinion leader*. Opinion leaders are people who you trust because they appear to be authoritative or because you agree with them on other issues. They might include a family member or influential friend, a media figure such as talk show hosts Tucker Carlson or John Oliver, or an influential politician such as Barack Obama or Donald Trump. In the absence of a strong opinion of your own, you can simply adopt the view of your opinion leaders. The problem with this approach is that many opinion leaders promote scientific viewpoints carefully screened to lend support to their preferred policies. Because of this, much of what you hear from opinion leaders is absolute nonsense.

1.4.1 How Science Works

Where should you turn to find out whether science supports a particular scientific claim? To answer this, let's discuss how science actually generates knowledge. Science begins with the process that most of you learned in high school, which may have been described to you as the "scientific method." It describes a process whereby an individual scientist generates a hypothesis, performs experiments to test the hypothesis, and then reaches a conclusion about the hypothesis.

In reality, this is only the first step of the true scientific process. Before the conclusion of this experiment can be considered "true," it must first be judged valid by the rest of the scientific community. This begins with the experimenter writing up a detailed description of exactly how the experiment was performed, the data that was collected, and the calculations or other methods of analysis that were done, all in enough detail that someone knowledgeable in the field could reproduce the work.

The resulting manuscript is then submitted for publication in a scientific journal. The first formal control that the scientific community exercises on the quality of scientific work comes at this point. Scientific journals will not publish the paper until it has been critically reviewed by other experts in the field. In this process, known as *peer review*, the reviewers' job is to look for errors or weaknesses in the analysis that might cast doubt on the conclusions. The identity of the reviewers is typically not revealed to the author, so that the reviewers can give their unvarnished opinion of the work without fear of later retribution.

If the reviewers do not identify any problems in the paper, then it gets published in the peer-reviewed literature. Peer review is a highly effective filter that stops many errors from being published, but it cannot catch every problem. Reviewers occasionally fail to notice an obvious mistake, and there are some types of error that reviewers cannot catch. They cannot tell if the author misread observations of an instrument, wrote a number down wrong, had a bug in their computer code, or if the chemical samples used in an experiment were contaminated.

But peer review is only the first level of quality control applied to scientific claims. When an important or novel claim passes peer review and is published in the peer-reviewed

literature, it then gets tested in what I call the “crucible of science.” This is the process whereby important conclusions get re-tested by the scientific community. This might mean having other scientific groups replicate the original experiment by re-doing the process described in the original peer-reviewed paper. This is important because, while one scientist might make a mistake, do a sloppy experiment, or have a bug in their computer code – and peer reviewers might fail to catch it – it is unlikely that multiple independent groups will make the same mistakes. Consequently, as other scientists confirm the results of the original experiment, the scientific community increasingly comes to accept the claim as correct.

Scientists can also test the implications of a scientific claim. For example, if someone claims the Earth is warming, we would expect that ice all over the world should be melting. That’s a testable hypothesis, and if it turns out to be true (it is), then that would increase our confidence in the conclusion that the Earth is warming. Naturally, all of these replications and other tests of the original claim will themselves be published in the peer-reviewed literature, so the peer-reviewed literature contains both the original claim as well as all attempts to re-test it.

Over time, as the peer-reviewed literature fills up with replications and other tests of a claim, some claims become well-verified enough that they come to be regarded simply as scientific truth. When this happens, we say that a *scientific consensus* on that claim has emerged. For example, we now accept as scientific truth that the structure of DNA is a double helix, that atoms obey the laws of quantum mechanics, and that burning fossil fuels has increased the abundance of carbon dioxide in the atmosphere. At this point, further investigation into these claims attracts little attention from the scientific community. If the evidence supporting a claim is mixed, with some evidence supporting it while other equally persuasive evidence contradicts it, then we would conclude there is no consensus on whether the claim is true or false.

The road to scientific consensus is not a clean, straight line. When a claim is novel, the peer-reviewed evidence is often mixed, with some peer-reviewed papers confirming and others dissenting. However, over time, as our understanding of a phenomenon grows, the scientific community may resolve these differences and develop a strong scientific consensus about the claim. It is important to point out that this is not a formal process. There are no meetings or votes where it is determined what the consensus is. Every scientist working in the field has their own ideas about what is well known and what is yet to be resolved in their field. Scientific consensus emerges organically when most scientists working in an area independently conclude that a particular scientific claim can be confidently categorized as either true or false.

Scientists who continue to dispute the consensus – and who can’t advance a good reason for doing so – become marginalized and ignored by their colleagues. In climate science, these people are sometimes referred to as *climate skeptics* or, less charitably, climate deniers. This latter term gains rhetorical power by comparing them to people who cast doubt on the reality of the Holocaust.

The messy development of scientific consensus gives dishonest advocates the opportunity to selectively cite out-of-date, discredited, or unrepresentative peer-reviewed

studies in an attempt to claim that “scientists disagree” on important questions, even when there is actually widespread agreement in the scientific community. In Chapter 13, we’ll talk in more detail about strategies advocates use to attempt to cast doubt on solid, well-understood science. These strategies were pioneered by the tobacco industry in the 1960s during their attempt to cast doubt on the solid science connecting smoking to various health impacts.

It is important to reiterate that a scientific consensus is not based on a poll or vote of the opinions of scientists, but rather an analysis of the published peer-reviewed literature. These should be similar because it is the scientists who are writing the papers, but it is nevertheless an important operational distinction. If I ask whether there is a consensus among scientists on some issue, how do you determine if consensus exists, and whose opinion counts? If, on the other hand, I ask whether consensus exists in the peer-reviewed literature, then it’s easy to determine what the consensus is – just read the scientific literature.

1.4.2 Scientific Assessments

While this sounds simple in theory – all you have to do is read the scientific peer-reviewed literature! – anyone who has ever tried to read a peer-reviewed journal article knows that it is extremely difficult. Scientific papers are densely written and full of jargon because they are written for other experts, so they assume a deep technical background and knowledge of the issue. Because of this, reading and understanding the peer-reviewed literature takes years of study, so it is impractical to expect non-experts to do that.

What we therefore need is a reliable summary of the peer-reviewed literature that is understandable to non-experts. The summary should focus on questions that are important to policymakers – for example, is the Earth warming, are humans to blame, what are the impacts? The report should then summarize what the peer-reviewed literature tells us about each one. It should also evaluate how confident we are about each conclusion, based on the level of consensus in the peer-reviewed literature, and communicate this to the assessment’s readers.

Such a summary of the peer-reviewed literature is what is known as a *scientific assessment*. Policymakers can turn to these assessments in order to determine what the science says on any particular scientific claim. These assessments do not perform new science – their job is simply to summarize and analyze the peer-reviewed literature in language that non-experts can understand.

Assessments start with policymakers defining the questions they want answered. Then, a writing team with relevant scientific expertise is assembled. The reliance on large writing groups reduces the possibility that an erroneous minority opinion will make it into the report, much like getting multiple opinions in medicine reduces the chance of a bad diagnosis. After the writing team produces its assessment, the assessment is then itself peer reviewed by other experts in the field. This provides an additional check to ensure that the assessment accurately summarizes the peer-reviewed literature.

The most well-known assessments of climate science are done by the Intergovernmental Panel on Climate Change, known by its initials IPCC. Formed in 1988, as nations began to acknowledge the seriousness of the climate problem, the IPCC writes comprehensive reports that summarize what we know about the climate and how confidently we know it. Their first report was in 1990 and reports have been published about every 6–7 years since then.

The IPCC makes enormous efforts to produce the most unbiased assessments of climate science. For example, to minimize the possibility that the writing team is biased in some direction, the scientists making up the writing teams are not assembled by a single person or organization; rather, they are assembled from nominations made by the world's governments. Thus, the only way the IPCC's writing groups would be biased in some direction is if all of the world's governments nominated individuals biased in the same direction. That seems unlikely since different governments have different perspectives on the seriousness of the climate problem.

The key point here is that assessments are only as credible as the process used to create them. Because of the strength of the process that the IPCC goes through to produce robust, unbiased reports, the IPCC's assessments are widely regarded as the most authoritative statements of scientific knowledge about climate change. This is one reason the IPCC shared the 2007 Nobel Peace Prize in recognition of its work assessing climate science.

But its high profile in the climate debate also means that those opposed to action to stabilize the climate have expended a lot of effort trying to discredit the IPCC. In all cases, the arguments against the IPCC are exaggerated and do not call into question the main messages from the assessments. Nevertheless, given the importance of the climate problem, it is worth pointing out that there have been many other assessments written by other credible organizations that reach exactly the same conclusions as the IPCC. The US National Academy of Sciences is one such organization. It was set up by Abraham Lincoln specifically to answer difficult science questions for the nation, and it has also put out assessments that agree with the IPCC's. So has the UK Royal Society. Links to these assessments can be found on this book's website.⁴

NASA, NOAA, and the National Science Foundation are all on record agreeing with the IPCC's conclusions. Scientific organizations like the American Meteorological Society and the American Geophysical Union also have statements in agreement with the IPCC's conclusions. It would require a conspiracy of ridiculous proportions to believe that all of these groups are lying in order to advance some political agenda.

Given this, I can now answer the question I posed at the beginning of this section: why you should believe this book. The reason is that the information in this book is based on assessments from the IPCC and other credible organizations, which in turn are based on the peer-reviewed literature. So this book represents not just my opinion of climate science – it's the opinion of the expert scientific community.

⁴ www.andrewdessler.com/chapter1

Aside 1.1: The Summary for Policymakers

The IPCC reports are summaries of the peer-reviewed literature, but they still run to thousands of pages. That is why every report also has a Summary for Policymakers, a more readable summary of the full report a few dozen pages long. Often referred to as the “SPMs,” they summarize in more general language the most important conclusions in the main report.

The SPMs also serve another unique function. During a final meeting after the main report is written, IPCC representatives from each of the world’s governments review a draft SPM written by scientists and vote on every sentence. Only if there is unanimous agreement from all of the world’s governments is a sentence included in the SPM. During this process, sentences are sometimes rewritten to make them unanimously acceptable to the world’s governments. If there is nearly unanimous agreement on a sentence, with just one or two countries dissenting, then the sentence can be included in the SPM with a footnote recording the dissent.

The purpose of this exercise is to produce a common set of scientific facts to serve as the basis of future negotiations on policy. By having unanimous agreement on every sentence, no country can later say during policy negotiations that they don’t agree with a particular scientific fact – they have already agreed to everything in the SPM.

This means, though, that every country is also trying to mold the SPM to best suit their negotiating position. During the meeting to approve the SPM for the IPCC’s 1995 report, for example, Saudi Arabia and Kuwait argued strenuously to weaken the statements about humans causing climate change. When the rest of the world disagreed, it was then proposed that a footnote would be added to the report noting the disagreement – but the footnote was removed at Saudi Arabia and Kuwait’s request because it would have been embarrassing for those two major oil producers to be the only countries in the world to not accept the scientific evidence of human impacts on climate.

In the end, the SPM represents a good summary of our scientific understanding of the climate but one that has an unavoidable hint of political influence in it. To the extent that political wrangling affects the SPM, it is almost always to water down the conclusions – reduce our confidence in scientific statements, lessen the impacts, etc. But despite these flaws, the SPMs are a good summary of what we know about climate change.

1.5 Chapter Summary

- *Weather* refers to the exact state of the atmosphere at a point in time; *climate* refers to the statistics of the atmosphere over a period of time, usually several decades in length or longer.

- Climate change refers to a change in the statistics of the atmosphere over decades. Such statistics include not just the averages but also the measures of the extremes – how much the atmosphere can depart from the average.
- Temperatures expressed in this book are in degrees Celsius; conversion from Fahrenheit can be done with this equation: $C = (F - 32) \times 5/9$.
- Any position on the surface of the Earth can be described by a latitude and longitude. Latitude is a measure of the position in the north–south direction, while longitude is a measure of the position in the east–west direction. The tropics cover the region from 30°N to 30°S; mid-latitudes cover the region from 30° to 60° latitude in each hemisphere; and the polar regions cover from 60° to 90° latitude in each hemisphere.
- Science produces knowledge through a three-step process. The first step is the individual scientist generating a hypothesis, testing it, and then reaching a conclusion. The next step is that this analysis undergoes peer review. If the paper passes, it is published in the peer-reviewed literature. The last step is the “crucible of science,” where claims are replicated, and their implications are tested.
- The truth or falsity of any scientific claim can be established by reading the peer-reviewed scientific literature and determining the extent to which claims have survived multiple replications and re-testing. In this way, one can evaluate how confidently the scientific community views any claims.
- Claims that have survived multiple replications and re-testing are often thought of as scientific truth. We can also say that there is a scientific consensus on this claim.
- It is difficult for non-experts to read the scientific literature. Therefore, policymakers and other non-experts rely on scientific assessments, reports written by scientists that summarize the peer-reviewed literature in a form that is understandable by non-experts.
- The most important assessments for climate science come from the Intergovernmental Panel on Climate Change (IPCC).

ADDITIONAL RESOURCES

The IPCC's scientific assessments are available online from www.ipcc.ch.

The US government does its own climate assessment about the impacts of climate change on the United States, known as the National Climate Assessment. You can find the 2018 report here: <https://nca2018.globalchange.gov/>

The UK Royal Society also has published reports and statements about climate change. You can find them here: <https://royalsociety.org/topics-policy/projects/royal-society-climate-change-briefings/>

See www.andrewdessler.com/chapter1 for links to the above material and additional resources for this chapter.

TERMS

Climate
Climate change
Climate skeptics
Equator
Latitude
Longitude
Mid-latitudes
Opinion leader
Peer review
Polar region
Scientific consensus
Summary for Policymakers
Tropics
Weather

PROBLEMS

1. Determine the latitude and longitude of the White House, the Kremlin, the Pyramids of Giza, and the point on the opposite side of the Earth to where you were born. Use an online tool (e.g., Google Earth) or an atlas (which you can find in any library).
2. (a) Convert the following temperatures from degrees Fahrenheit to degrees Celsius: 300, 212, 70, 50, 32, and 0°F.
(b) Convert the following temperatures from degrees Celsius to degrees Fahrenheit: 150, 100, 70, 50, 0, and -10°C .
3. (a) The temperature increases by 1°C . How much does it increase in degrees Fahrenheit?
(b) The temperature increases by 1°F . How much does it increase in degrees Celsius?
(c) This is true: I told a reporter that the Earth has warmed by 0.8°C over the last century. When it appeared in print, the sentence said: “Dessler said that the Earth has warmed by 33°F over the last century.” What did the reporter do and why was it wrong?
4. What temperature has a numerical value that is the same in degrees Celsius as it is in degrees Fahrenheit?
5. Find a two-digit temperature in degrees Fahrenheit for which, if you reverse the digits, you get that same temperature in degrees Celsius (e.g., find a temperature, such as 32°F , for which the Celsius equivalent would be 23°C ; this example, of course, does not work).
6. Why do you believe that smoking causes cancer? (If you do not believe this, then why do you believe that smoking does not cause cancer?) What would be required to get you to adopt the opposing view?

7. Find two friends who have strong but opposing views of climate change.
 - (a) Ask both of them why they believe what they do and what would be required for them to adopt the opposing view. It is important to understand where their views come from; if they argue, say, that glaciers are retreating or not, find out where they get their facts.
 - (b) Which of these positions appears more credible? Why?
 - (c) Can you use their views on climate change to predict their views on other issues (abortion, gun control) and their political affiliation?
8. Practice reading a graph. These questions all refer to Figure 1.1.
 - (a) What fraction of days have a daily high temperature of 28°C during the 1970s and the 2010s?
 - (b) For the 1970s and 2010s, what is the most likely temperature? How much did it increase over this period?
 - (c) What temperature(s) have an equal probability of occurring in the two periods?
 - (d) For the 1970s and 2010s, estimate the fraction of days that have a temperature 35°C or greater.
 - (e) What does this tell you about the changes in extreme heat under even modest warming?
9. Give examples of situations when weather affected your or your family's life. Then do the same for climate.
10. Those opposed to the IPCC's scientific conclusions have set up their own summary of the science of climate change, which they call the NIPCC. Do some online research and then compare and contrast the credibility of the two reports.
11. In the climate debate, few institutions are attacked as frequently as the IPCC. Using web searches, identify some arguments made by those arguing that the IPCC cannot be trusted.
12. You are the President of the United States. A novel virus has appeared, and two trusted advisors are giving you contradictory claims about how bad it is. One says it's no worse than the flu, the other says it's far worse. They can't both be right. What questions would you ask them in order to determine which claim is correct?
13. Donald Trump says that the wildfires in California in 2020 were caused by forest management while Joe Biden says it's due to climate change. Whose statement do you believe and why? Do you think your views are supported by science?

2

Is the Climate Changing?

In this chapter, I address the questions of whether the Earth's climate is currently changing and how it has changed in the past. You will see overwhelming evidence that the climate is indeed changing and that it has changed significantly over the Earth's entire history. I will not discuss the causes of climate change here, though – we will do that in Chapter 7.

In Chapter 1, climate change was defined as a change in the statistics of the weather, normally over a period of several decades. In this chapter, the statistic I will primarily focus on is global average temperature for two reasons. First, the most direct impact from the addition of greenhouse gases to the atmosphere is an increase in temperature. Changes in other aspects of climate, such as precipitation or sea level, are a response to the temperature change. Second, we have the best data for temperature. The technology for measuring it is centuries old, and people have been measuring and recording the temperature with sufficient global coverage since the middle of the nineteenth century. In addition to direct temperature measurements, there are other techniques, such as studying the chemical composition of ice and rocks, that allow us to indirectly infer the temperature of the Earth over much of its 4.5-billion-year history.

I will also focus in our discussion on global average quantities. The reason is that the climate of a region can vary significantly just due to weather variability – i.e., particular regions can experience climate extremes (e.g., a heat wave) that are completely unrelated to climate change. However, these local variations are usually balanced by an opposite extreme elsewhere: if one region is undergoing a heat wave, there is likely another region that is undergoing a cold wave. By averaging over the globe, we rid ourselves of most of this weather variability and more clearly isolate the climate change signal.

2.1 Temperature Anomalies

As you can probably imagine, measuring the planet's temperature is not a trivial exercise. The main issue is that temperature can vary sharply over short distances as the local environs change. Areas with a lot of concrete tend to be warmer than areas with more vegetation, so as you walk from an asphalt parking lot to a nearby tree-covered park on a sunny day, you can literally feel the temperature change.

In order to measure the *absolute* temperature, one would therefore need a very dense thermometer network. In some areas of widely varying composition, thermometers may need to be located every few tens of meters. Such a dense network is completely impractical,

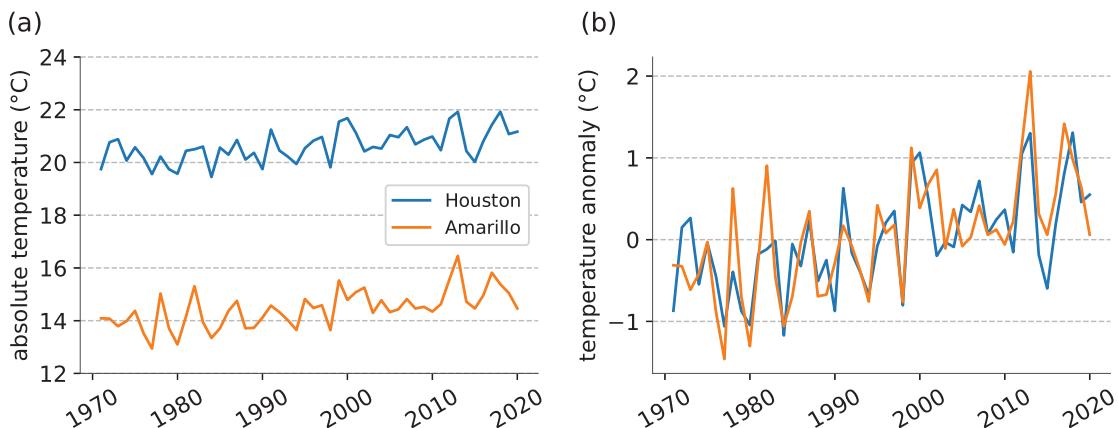


Figure 2.1 (a) Annual temperatures ($^{\circ}\text{C}$) in Houston, TX (Bush-IAH station) and Amarillo, TX (Amarillo International Airport station). (b) Temperature anomalies ($^{\circ}\text{C}$) at these stations, relative to the 1980–2010 average. Data are derived from breakpoint-adjusted monthly station data from Berkeley Earth (<http://berkeleyearth.org/data/>, retrieved May 21, 2020).

so scientists instead analyze *temperature anomalies*, defined as the difference between the absolute temperature and a reference temperature.

As an example, let's start by examining annual temperatures at two stations in Texas, Houston and Amarillo, over the past few decades (Figure 2.1a). As you might expect, the temperatures in these two cities, located about a thousand kilometers apart, are not the same — Houston is quite a bit warmer, owing mainly to warmer wintertime temperatures due to its proximity to the Gulf of Mexico.

To calculate temperature anomalies for Houston and Amarillo, we first need to calculate a reference temperature for each location, typically the average temperature over a previous multi-decadal period. For this example, we'll pick the 1980–2010 average as our reference period. The average temperature in Houston over this period was 20.6°C , and in Amarillo it was 14.4°C . We then subtract these reference temperatures from each year of the corresponding time series, and we get the temperature anomaly time series in Figure 2.1b.

This is a remarkable result because it shows that, despite the great distance between these cities, their anomalies are very similar: If Houston had a temperature anomaly of $+1^{\circ}\text{C}$ in a particular year, then Amarillo would also tend to have a temperature anomaly of $+1^{\circ}\text{C}$, even though the absolute temperatures differ by quite a bit. This leads us to the remarkable conclusion that *you would only need one thermometer* to measure the annual temperature anomaly of a large region running across much of Texas.

Scaling this up to the globe, scientists have calculated that you need about 100 thermometers distributed around the globe to accurately measure the global average temperature anomaly. This is the primary reason that the scientific community focuses on anomalies rather than absolute temperatures and, in this book, we will do so too.

2.2 Recent Climate Change

2.2.1 Surface Thermometer Record

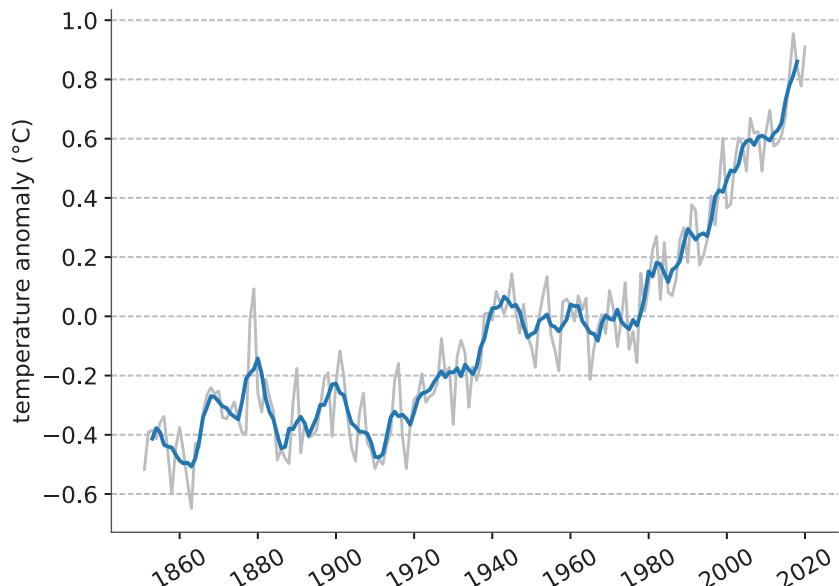
We have had sufficient coverage of the Earth since the middle of the nineteenth century to estimate the global average temperature anomaly from thermometers distributed across the surface of the planet, and that time series is plotted in Figure 2.2. The data show that the Earth has warmed by 1.10°C over this time (calculated as the difference between the 1850–1900 average and the 2009–2018 average).

This doesn't sound like much warming, but, as we'll see in Chapter 9, it is. And in Chapter 8, we'll see that predicted warming for the twenty-first century is several times the warming in Figure 2.2. If that comes to pass, it will be very bad for those living through it, which I imagine includes many of the people reading this book.

The warming has not been uniform in time, with little warming occurring between 1940 and 1975. Superimposed on the slow warming trend are many bumps and wiggles, which are unrelated to climate change. Despite this short-term variability, the warming since the 1970s is basically continuous, with every decade warmer than previous decades. As I write this in early 2021, the six warmest years in the record were 2016, 2020, 2019, 2017, 2015, and 2018. The ten warmest years have all occurred after 2005. In fact, I can confidently predict that every future year for the rest of your life will be one of the hottest in the record.

Figure 2.3a shows how the warming in Figure 2.2 is distributed across the planet. The warming is occurring just about everywhere – thus justifying the “global” part of “global warming.” However, the warming has not been uniform. One clear difference is that land areas warmed more than the ocean. It is also clear that the northern hemisphere warmed more than the tropics or the southern hemisphere (Figure 2.3b). This is important because

Figure 2.2 Global annual average temperature anomaly ($^{\circ}\text{C}$); the gray line is the annual average, and the blue line is a smoothed time series. Anomalies are calculated relative to the 1951–1980 average. Data are from Berkeley Earth (<http://berkeleyearth.org/data/>, retrieved September 27, 2020).



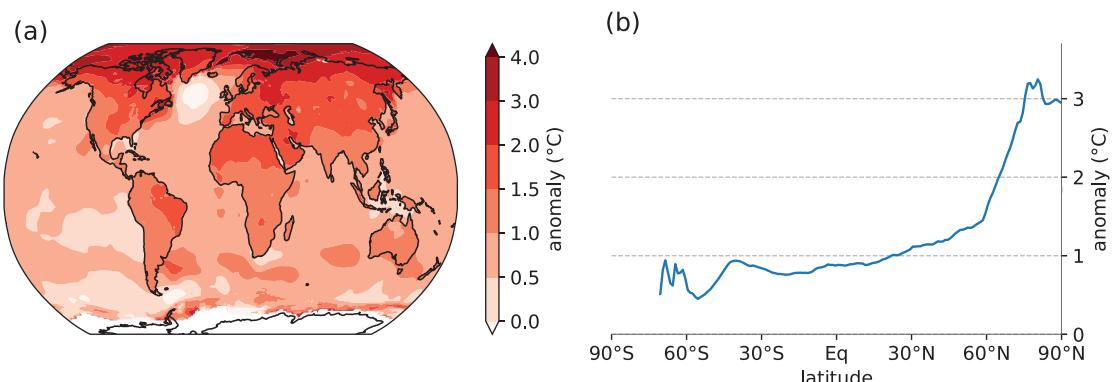


Figure 2.3 The distribution of modern warming (in °C). (a) Spatial distribution of the warming; (b) the warming as a function of latitude. Warming is calculated as the difference between the 1850–1900 average and 2009–2018 average. Data are from Berkeley Earth (<http://berkeleyearth.org/data/>, retrieved October 14, 2020).

most people live on land in the northern hemisphere, meaning that they are experiencing more warming than the global average seen in Figure 2.2.

One must look at any single data set skeptically. This network of thermometers was not designed for climate monitoring, and, over the years, the network has undergone many changes. Changes in the types of thermometer used, station location and environment, observing practices, and other sundry alterations all have the capacity to introduce spurious trends in the data.

For example, imagine you have a thermometer that is in a rural location in the late nineteenth century. Over time, a nearby city expands so that by the 1980s, the thermometer is completely surrounded by the city. Because cities tend to be warmer than nearby rural locations, this would introduce a warming trend in the data not caused by a warming climate.

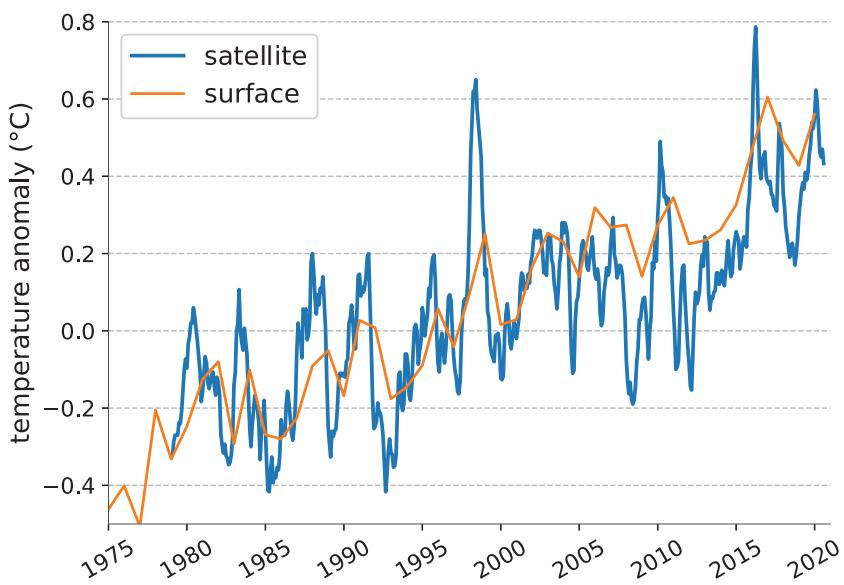
Scientists know about these problems, and, to the extent possible, adjust the data to take them into account. For example, the impact of a city growing up around a thermometer can be assessed by comparing the measurements from that thermometer to nearby thermometers that have remained rural for the entire period. The temperature record in Figure 2.2 includes adjustments to account for as many of these issues as possible. It should be emphasized that these adjustments, while potentially large regionally, are small in the global average.

Given the importance of the conclusion that the Earth is warming and the potential limitations of these data, it would be foolish to rely entirely on just this one data set. Scientists therefore turn to other observations to verify this result. In the rest of Section 2.2, I describe the other data sets used to build confidence in the surface thermometer data set.

2.2.2 Satellite Measurements of Temperature

It is possible to measure global average temperature from orbit, and the United States has been flying instruments on satellites to make that measurement since 1978. Figure 2.4 shows

Figure 2.4 Satellite measurements of the global monthly average temperature anomaly ($^{\circ}\text{C}$) (blue line). The orange line is annual average temperature ($^{\circ}\text{C}$) from the surface thermometer record plotted in Figures 2.2 and 2.3. Anomalies in this plot are relative to the 1981–2010 period. Satellite data were obtained from the University of Alabama, Huntsville (http://vortex.nsstc.uah.edu/data/msu/v6.0/tlt/uahncdc_lt_6.0.txt, retrieved September 27, 2020).



the time series of satellite measurements of the global monthly average temperature anomaly. These data show a general warming trend over this period of approximately 0.13°C per decade (1.3°C per century).

As with all data sets, though, this one has its own set of problems and uncertainties. First, satellites actually measure the average temperature of the lowest 8 km of the atmosphere, from the surface to about the altitude where airliners fly. Thus, it is not actually a measurement of the surface temperature, although the temperature of this layer of the atmosphere should track the surface temperature.

Another issue with these data is orbital drift of the satellites carrying the instruments. Imagine that a satellite flies over a location at 2 PM each day and makes a measurement of that location's temperature. Over time, the satellite's orbit drifts so that it flies over that location later and later each day. After a few years, the satellite is flying over that location at 3 PM. Because temperatures rise throughout the day, it is generally warmer at that location at 3 PM than it is at 2 PM. Thus, the drift in the satellite's orbit would by itself introduce a warming trend, even if the climate were not actually changing. This artifact must also be identified and adjusted for.

Other issues include calibration of the satellite instruments, which were never designed to make long-term measurements, and the shortness of the satellite record (just a few decades long), both of which also introduce uncertainty into the observed warming. As with the surface thermometer record, these issues are known and adjusted for, to the extent possible.

One way to gain confidence in the satellite and surface thermometer records is to compare them; this is done in Figure 2.4. The excellent agreement between these two independent temperature measurements provides strong confirmation of the reality of the warming of the climate seen in both data sets.

Aside 2.1: Has global warming stopped?

...the planet has largely stopped warming over the past 15 years, data shows. – FoxNews.com, September 27, 2013¹

In the early 2010s, one popular argument made by those attempting to cast doubt on climate science was that the Earth had been warming, but the warming had stopped. The implications of this were two-fold: First, climate science hadn't predicted this stoppage, so it showed that scientists have no idea what's going on with the climate. Second, the cessation of global warming suggested that future climate change is also nothing to worry about.

So did climate change stop between the late 1990s and early 2010s? Figure 2.4 showed that superimposed on the slow warming trend are lots of short-term bumps and wiggles. These are not random but can be assigned to various physical causes, mainly El Niño–La Niña cycles and volcanic eruptions. During El Niño events, the Earth warms several tenths of a degree Celsius. El Niño's opposite is La Niña, and during those events the Earth cools several tenths of a degree. Volcanic gases emitted during eruptions cool the climate by blocking sunlight – after a few years, the effluents are removed from the atmosphere and the climate returns to normal. These processes will be discussed in more detail later in the book.

These sources of short-term variability do not have anything directly to do with climate change and do not cause any long-term changes in the climate. The bumps and wiggles do, however, make determining trends over short time periods (e.g., a decade) problematic. To illustrate this, Figure 2.5 shows monthly average global surface temperature anomalies between 1970 and 2020. Over this period, the planet warmed rapidly, at a rate of $1.7^{\circ}\text{C}/\text{century}$.

Also shown on Figure 2.5 are short-term trends based on endpoints that were carefully selected to produce cooling trends. As you can see, it is possible to generate a continuous set of short-term cooling trends, even as the climate is experiencing a long-term warming. All you have to do is start the trend calculation during a particularly hot year (e.g., an El Niño year) and then end it in a cool year (e.g., a La Niña or volcanic year).

¹ <https://web.archive.org/web/20210530025736/https://www.foxnews.com/science/un-climate-change-report-dismisses-slowdown-in-global-warming>, accessed May 29, 2020.

Aside 2.1 (cont.)

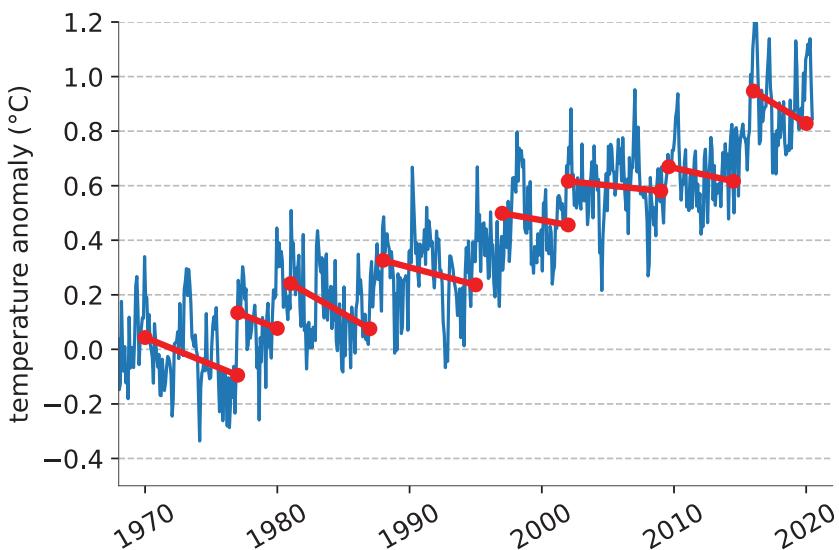


Figure 2.5 A plot of monthly and global average surface temperature ($^{\circ}\text{C}$) from the surface thermometer record (blue line) along with short-term trend lines (red lines). This figure is an adaptation of SkepticalScience's escalator plot (www.skepticalscience.com/graphics.php?g=47). Data are from Berkeley Earth (<http://berkeleyearth.org/data/>, retrieved September 28, 2020).

The existence of these short-term negative trends allows someone to disingenuously claim in almost any year covered that global warming had stopped or even that the Earth had entered a cooling period – despite the obvious rapid warming occurring over this period. There is even a term for this deceptive argument: “Going down the up escalator.”

There are two lessons here. First, claiming that global warming has stopped requires careful selection of the endpoints. This process of intentionally selecting data to yield a result counter to the full data set is known as *cherry picking*. Many of the skeptical claims you will hear in the public debate over climate are based on cherry picking a large data set in order to find the small number of exceptions that allow one to claim the opposite of what the entire data set shows.

Second, it is only possible to find cooling over short time periods. Over periods lasting several decades, the long-term warming dominates, and even the most egregious endpoint selection cannot generate a cooling trend. We will return to this point when we talk about climate predictability in Section 8.5.

Ultimately, you should be skeptical about claims you hear in the public debate over climate change. If someone says something that seems ridiculous, it may well be. When in doubt, you should turn to authoritative sources like assessments from the IPCC or the US National Academies. These assessments were generated by a credible process and contain the best summary of the scientific evidence of climate change.

So two independent, direct measurements of temperature show the planet is warming, but this question is so important that even more confirmation is required. To do this, we turn to other measurements that, while not direct measurements of temperature, nevertheless tell us something about the temperature of the planet: the amount of ice on the planet, the heat content of the ocean, and sea level.

2.2.3 Ice

Because ice melts reliably at 0°C, it is a dependable indicator of temperature. In particular, if the warming trend identified in the surface thermometer and satellite records is correct, then we should expect to observe the Earth's ice disappearing. In this section, I show that ice around the world is indeed disappearing, thus confirming the warming seen in the other data sets.

2.2.3.1 Glaciers

Glaciers form in cold regions when snow that falls during the winter does not completely melt during the subsequent summer. As snow accumulates over millennia, the snow at the bottom is compacted by the weight of the overlying snow and turns into ice. This process eventually produces glaciers hundreds, or even thousands, of feet thick.

The length, areal extent, and total volume of glaciers have been monitored for decades and, in some cases, centuries. Figure 2.6 shows the change in glacier mass over the last half century. It shows that glaciers are indeed losing ice, just as we would expect in a warming climate indicated by Figures 2.2 and 2.3. Note that the mass units in Figure 2.6 are tonnes, where a tonne is a metric ton, 1,000 kg. I will use this unit frequently throughout the book.

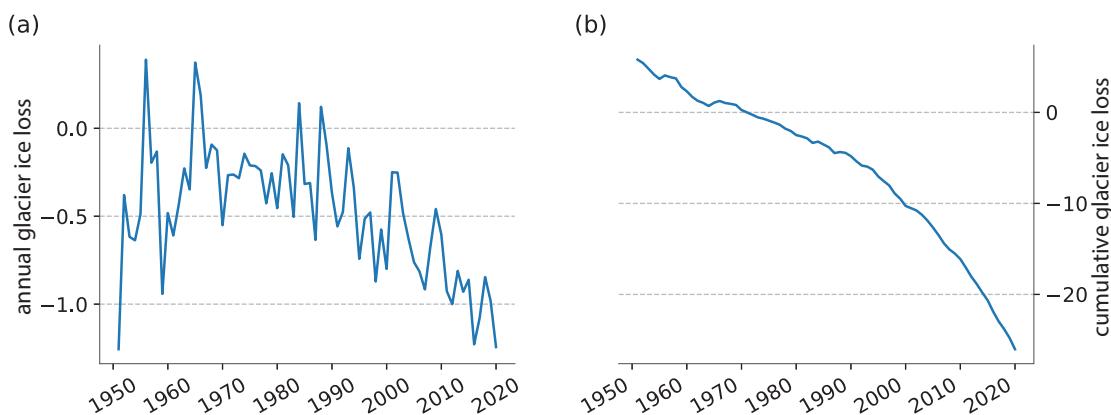


Figure 2.6 (a) Global average annual change in mass of the world's glaciers, in tonnes/m²/year. (b) Global average cumulative mass change, in tonnes/m². Given that ice has a density of about 0.9 tonnes/m³, a loss of 1 tonne of ice/m² is equal to the loss of about 1.1 m of glacier ice thickness. Data from WGMS (2020) (obtained from <https://wgms.ch/global-glacier-state/>, retrieved November 26, 2020).

2.2.3.2 Sea Ice

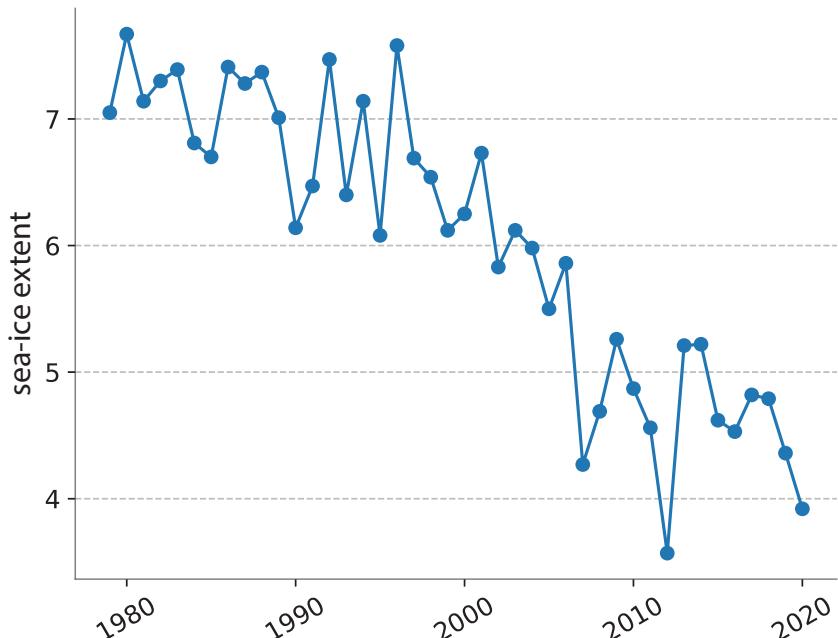
At the cold temperatures found in polar regions, seawater freezes to form a layer of ice, typically a few meters thick, floating on top of the ocean. The area covered by sea ice varies over the year, reaching a maximum in late winter and a minimum in late summer. Given the rapid warming now occurring, particularly in the Arctic, we would expect to see reductions in the area covered by sea ice, particularly during the summer. Figure 2.7 confirms a clear downward trend in the area covered by Arctic sea ice at the end of the summer. Measurements also show that, in addition to shrinking in area, sea ice has grown thinner.

The Antarctic is a different story. The sea-ice area around that continent has remained stable since the mid-1970s, although the late 2010s had a few years with significant declines. This overall pattern – large losses of sea ice in the Arctic and less loss in the Antarctic – matches the regional temperature trends in these regions (Figure 2.3), which show large, rapid warming in the northern hemisphere and weaker warming in the southern hemisphere. In this way, the sea-ice data confirm not just the overall warming trend but also the distribution of the warming over the globe.

2.2.3.3 Ice Sheets

The Earth has two major ice sheets, one in the northern hemisphere, on Greenland, and the other in the southern hemisphere, on Antarctica. Although these ice sheets are really just big

Figure 2.7 Arctic sea-ice area (in millions of square kilometers) in September of each year. Data from Fetterer et al. (2017). Sea Ice Index, Version 3.0 [Data sets ID NSIDC-0081 and ID NSIDC-0051]. Boulder, Colorado USA: National Snow and Ice Data Center. doi: <https://doi.org/10.7265/N5K072F8> (accessed on November 26, 2020).



glaciers, their sheer size puts them in a class by themselves: they cover millions of square kilometers, and in places they are more than 3,000 m thick (nearly 2 miles). These ice sheets contain the vast majority of the world's fresh water, and if they melted completely, the sea level would rise approximately 65 m (more than 200 ft).

Scientists can measure changes in the mass of the ice sheets by measuring changes in the ice sheets' height using space- and aircraft-borne laser altimetry or by measuring how these ice sheets alter the Earth's gravity. These show that both Greenland and Antarctica have been losing mass: Greenland has been losing around 250 billion tonnes of ice each year, while Antarctica has been losing about 180 billion tonnes per year.

Putting all these data together, we conclude that the amount of ice on the planet is decreasing. This is consistent with measurements of rising temperatures from surface thermometers and satellites and provides additional confirmation that the Earth is warming.

2.2.4 Ocean Temperatures

Much of the heat trapped by greenhouse gases goes into heating the oceans, so we can also look to see if the oceans are warming. I am not talking here about the surface temperature of the ocean – that is included in the surface thermometer record described in Subsection 2.2.1. Rather, I am talking about the temperature of the bulk of the ocean: the water temperature averaged over the entire depth of the ocean (the average depth of the ocean is 4 km). Scientists determine this temperature by lowering thermometers into the ocean, measuring the temperature at various depths, and then averaging these results to come up with a single average ocean temperature over that depth.

Most of the warming of the ocean is taking place in the top half. Measurements of the top 2 km of the ocean have been made for several decades, and Figure 2.8 shows the ocean's temperature anomaly over time. The ocean is indeed observed to be warming, and this provides another source of independent confirmation that the Earth is warming. While the amount of warming of the ocean appears small, water holds a tremendous amount of energy, so this seemingly small temperature increase actually represents an enormous accumulation of energy in the climate system.

2.2.5 Sea Level

Sea-level change is connected to climate change in two ways. One contributor is the melting of grounded ice. Grounded ice is ice that is resting on land. When it melts and the water runs into the ocean, the total amount of water in the ocean increases and sea level rises. This is different from the melting of floating ice. When floating ice melts, the melt water occupies roughly the same volume as was displaced by the ice (as shown by Archimedes), so there is little sea-level rise. We saw in Subsection 2.2.3 that we are losing grounded ice all over the planet, and we expect that to drive an increase in sea level. In addition, water, like most things, expands when it warms. We saw in Subsection 2.2.4 that the oceans are indeed warming, and the resulting thermal expansion should also raise sea level.

Figure 2.8 Ocean temperature anomaly ($^{\circ}\text{C}$) of the top 2,000 m of the world ocean. Anomalies are relative to the 1979–1994 mean. Data were obtained from NOAA National Centers for Environmental Information (www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/, retrieved November 26, 2020).

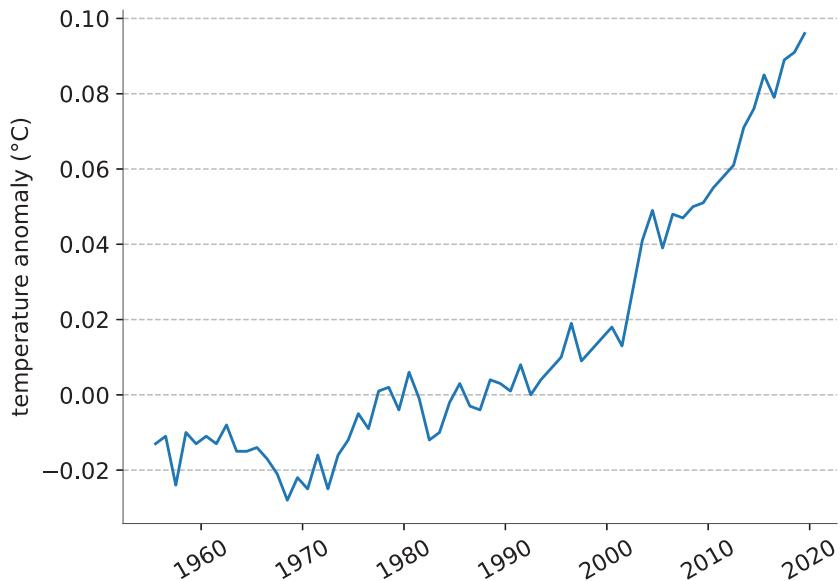


Figure 2.9 Change over time in global-average sea level, in millimeters. The seasonal cycle has been removed. Data are described by Nerem et al. (2010) (obtained from <http://sealevel.colorado.edu/>, retrieved on November 26, 2020).

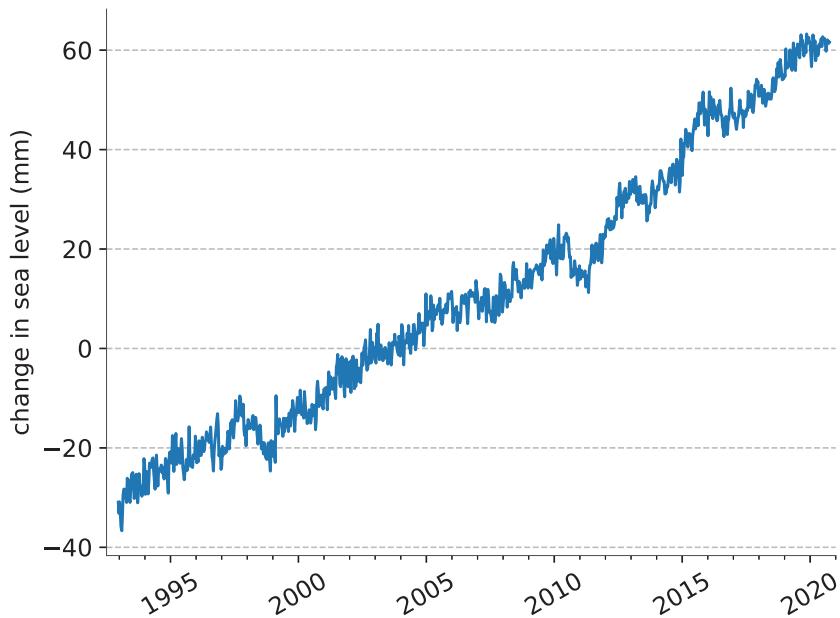


Figure 2.9 shows observations of sea level from satellites, which show, as expected, that sea level is rising. We can also estimate changes in sea level on longer time scales using tide gauges that go back to the beginning of the twentieth century. Between 1900 and 2018, global mean sea level rose by 0.19 m, corresponding to an average rate of sea-level rise of

1.6 mm/yr. This rate was faster than any century in the last 3,000 years. Between 1993 and 2018, the rate was higher still: 3.2 mm/yr. Thus, sea level is not just rising, the rate of increase is accelerating.

2.2.6 Putting It Together: Is Today's Climate Changing?

The answer is an emphatic *yes*. In fact, the evidence is so strong that the IPCC describes today's warming as "unequivocal" – meaning it is beyond doubt. It is worth exploring the source of high confidence in this conclusion. As I talked about in Chapter 1, the gold standard in science is multiple replication of results. The conclusion that the Earth is warming is one of the most replicated results in all of science. The surface thermometer record and the satellite record agree well, and both show that temperatures are rising. The loss of ice on the Earth's surface is consistent with these increasing temperatures, as is the increase in the heat content of the ocean. Finally, the observation of increasing sea level fits with all of the other observations.

These data sets are also fundamentally independent. For example, issues such as changes in the station environment, which may affect the surface thermometer record, do not affect the satellite record. Issues such as orbit drift affect the satellite record but do not affect the surface thermometer record. And neither of these problems affects the measurements of glacier mass or sea level. This means that there is no single problem or error that could introduce a spurious warming trend in all of the data. Because of this, 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.

In fact, the data don't just agree – they fit together like pieces of a jigsaw puzzle. We see significant ice loss in the Arctic, but not the Antarctic. This agrees with the surface temperature record, which shows much more warming in the Arctic than the Antarctic. We can also estimate how much sea-level rise there should be by adding estimates of the amount of water added to the ocean from melting of grounded ice to estimates of sea-level rise due to thermal expansion of the ocean. We find that this sum agrees almost perfectly with the measured sea-level rise. This internal consistency of the details of the warming provides strong additional evidence that it is actually occurring.

Finally, the data sources we have reviewed are just a small part of the mountain of evidence that the Earth is warming. There are literally thousands of observed physical, biological, and ecological changes that are consistent with warming. Not every data set shows warming, but such contrary data are rare, regionally limited, and vastly outnumbered by evidence of warming.

2.2.7 What Is Not Evidence of Climate Change

It is useful at this point to recognize what is *not* evidence of climate change. Because climate change is a shift in the statistics of the atmosphere, a single seemingly odd weather event is almost never evidence of climate change. A single extremely hot summer, for example, even

if it were hotter than any other summer of the past 100 years, might nonetheless occur in a stable climate. If hot summers were to begin to happen regularly, however, then that would be indicative of climate change.

Rather than look at single events, one should instead examine the statistics of the climate over time, as we have done in this section. In so doing, it is crucial that the statistics cover a sufficiently long period. Otherwise, the inference of climate change may be affected by the shortness of the data record.

It is also important to avoid drawing conclusions about the global climate from regional climate extremes. At any given time, it is unusually hot somewhere on the Earth and unusually cold somewhere else. So the existence of these regional extreme temperatures does not tell us much about climate change because regions experiencing hot and cold extremes will largely cancel each other. It is only after one averages over these regions that one can examine the residual to determine if the globe is warming or not.

So be careful when evaluating the evidence for and against climate change. Do not be misled by unlikely-seeming single events or by regional occurrences. Neither is indicative of a shift in the global climate.

2.3 Climate over the Earth's History

2.3.1 Paleoproxies

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, however, go back at most a few centuries, so other data sets are needed if we wish to look back any further. Such data sets are known as *paleoproxies*, which are long-lived geological, chemical, or biological systems that have the climate imprinted on them. In this way, we can make measurements *today* that tell us what the climate was like *in the past*.

For example, the ice in a glacier or ice sheet provides useful climate data dating back to the time when the snow fell. Remember that glaciers and ice sheets form when snow accumulates from one year to the next and is converted to ice by the weight of the overlying snow. The chemical composition of the ice holds important information about the air temperature around the glacier when the snow fell, as do variations in the size and orientation of the ice crystals. Small air bubbles trapped during the formation of glacial ice preserve a snapshot of the chemical composition of the atmosphere when the snow fell. In addition, the dust trapped in the ice gives information about prevailing wind speed and direction. And because more dust blows around during droughts, it also provides information about how wet or dry the regional climate was when the ice formed. Finally, because sulfur is one of the main effluents of volcanoes, measurements of sulfur in glacial ice show whether there was a major volcanic eruption around the time the ice formed.

To obtain all of this information, ice cores are obtained by drilling down into the glacier or ice sheet with a hollow drill bit and extracting a cylinder of ice a few inches in diameter and sometimes thousands of feet long. Reconstructing past climate information from an ice

core then requires two steps. First, the age of each ice layer must be determined from its depth inside the glacier. The deeper down the ice was obtained, the older the ice is and the further back in time for which it provides climate information. Much effort has been spent connecting a particular chunk of ice to an exact time, because the rate of ice accumulation varies over time and because ice inside a glacier can compress and flow under the weight of the ice above. Second, the characteristics observed, such as the abundance of chemicals in the ice, must be translated into the climatic characteristics of interest, such as temperature.

Obviously, ice cores only provide climatic information in regions and over time periods that are cold enough for permanent ice to exist. This includes Greenland, Antarctica, and glaciers found around the world. Ice cores from the thickest, oldest ice in Antarctica have provided information about the climate going back an amazing 2 million years.

Other paleoproxies provide data in other regions and over other time periods. For example, trees store climate information in their 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 fall, they produce dark wood. Because trees grow more, and produce wider rings, in warm and wet years, the width of each ring gives information about climate conditions around that tree in that year. By looking at the rings of a tree, scientists can therefore obtain an estimate of the local climate around the tree for each year during which the tree was alive.

Climate data from tree rings are only available for a fraction of the Earth's surface. They are obviously not available for oceans, or for desert or mountainous areas where no trees grow. They are also not available in the tropics, where the weaker seasonal cycle causes trees to grow year-round; those trees do not produce rings. Finally, tree rings only reveal information about the climate as far back as wood from them is available. This means that the tree ring records provide useful climate information for the past millennium or so.

Ocean sediments, which accumulate at the bottom of the ocean every year, also contain information about climate conditions at the time they were deposited. The most important source of information in sediments comes from the skeletons of tiny marine organisms. The relative abundance of species that thrive in warmer versus colder waters gives information about surface water temperature. The chemical composition of the skeletons and variations in the size and shape of particular species provide additional clues. In total, ocean sediments provide information about water temperature, salinity, dissolved oxygen, atmospheric carbon dioxide, nearby continental precipitation, the strength and direction of the prevailing winds, and nutrient availability; this information goes back tens of millions of years.

Putting all of these paleoproxies together gives us a reasonably complete picture of the global climate going back hundreds of millions of years, with some information about the climate going back billions of years.

2.3.2 The Earth's Long-Term Climate Record

Although most of the details of the climate during the first 97 percent of the Earth's history are unknown, there are a few things that we can say. We know that the oldest sedimentary

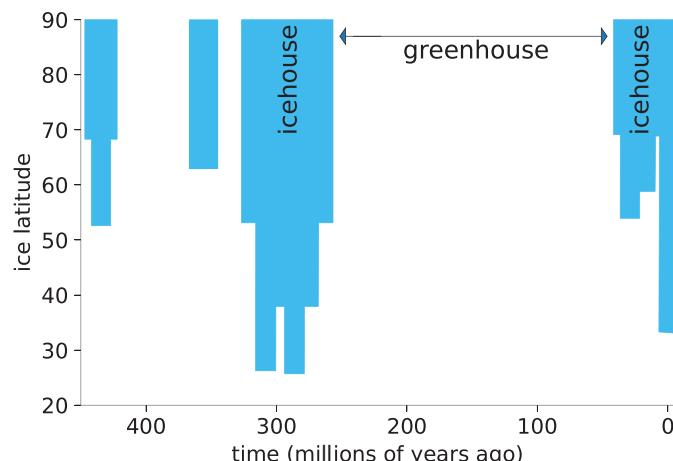
rocks on the planet are nearly 4 billion years old. Because sedimentary rocks generally form in the presence of liquid water, their existence suggests that the Earth has been warm enough over most of its history that water has remained mostly in the liquid phase.

There is also evidence of intervals of widespread ice cover. Approximately 700 million years ago, the Earth was covered by ice from the poles to near the Equator – a climate configuration now referred to as *snowball Earth*. Since then, the Earth has fluctuated between periods of large-scale glaciation and periods with little permanent ice on the planet (Figure 2.10). These two climate states, known as *icehouse* and *greenhouse* periods, respectively, last tens of millions of years. During icehouse periods, such as the period about 300 million years ago, ice frequently gets down to the latitude of the US Midwest (Figure 2.10). During greenhouse periods, such as the period between 250 million and 35 million years ago, the Earth is largely ice-free. We are currently living in an icehouse state, which began about 35 million years ago when the Antarctic ice sheet formed. *Important:* do not confuse the icehouse–greenhouse cycle with ice-age cycles, which we will discuss shortly.

Figure 2.11 shows a reconstruction of global temperatures over the past 70 million years derived from ocean sediments. The warmest temperatures in this record occurred approximately 50 million years ago – 15 million years after the extinction of the dinosaurs – in a period called the *Eocene Climatic Optimum*. The world was in a greenhouse state, and the planet was far warmer than it is today. Forests covered the Earth from pole to pole, and plants that cannot tolerate even occasional freezing lived in the Arctic, along with animals such as alligators that today live only in tropical climates. Since that time, the Earth has experienced a long-term cooling. Clearly, humans had nothing to do with either the warmth of the Eocene or the cooling since then; I will talk more about these climate variations in Chapter 7.

Figure 2.11 also shows the Paleocene–Eocene Thermal Maximum (marked as a “P” on the figure and frequently abbreviated PETM), which occurred 55 million years ago, at

Figure 2.10 Extent of continental ice deposits, showing icehouse–greenhouse cycles. The blue bars show the largest latitudinal extent of ice over time. Adapted from Figure 1 of Foster et al. (2017).



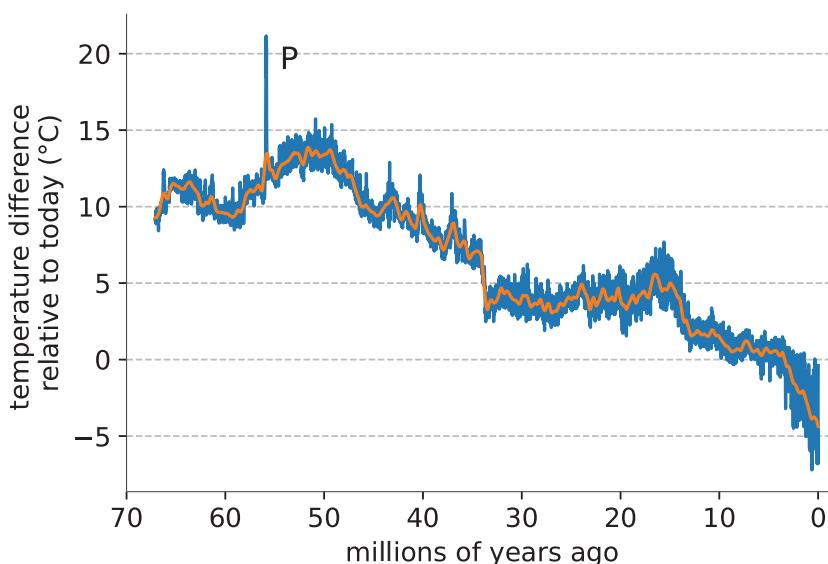


Figure 2.11 Reconstructed global average surface temperature over the past 70 million years, relative to today's temperature. The sharp temperature spike 55 million years ago (labeled “P”) represents the Paleocene–Eocene Thermal Maximum (PETM). This plot is adapted from Figure 1 and Table S34 of Westerhold et al. (2020).

the temporal boundary between the Paleocene and Eocene epochs. The PETM featured an abrupt warming of more than 5°C that occurred over a few thousand years. The temperature then slowly returned to pre-PETM temperatures over the next few hundred thousand years. It is believed that this was caused by a massive release of greenhouse gases; many scientists view this episode as a good analog to the warming event we are now in the midst of. We will use this event in later chapters to help us understand how humans might perturb the climate.

Figure 2.12a zooms in to show global temperature variations over the past 5.3 million years. Like the 70-million-year record in Figure 2.11, this record also shows a general cooling trend. This record, however, covering a more recent time, shows fine-scale details that are not visible in the longer record. Before about 3 million years ago (Figure 2.12b), temperatures were relatively constant and showed little variability.

After that, large ice sheets appeared in the northern hemisphere, and large oscillations between warmer and cooler periods suddenly appear in the record (Figure 2.12c). During the cool periods, called *ice ages*, the ice sheets expanded to cover large parts of the northern hemisphere's land areas. During the warm periods between the ice ages, called *interglacials*, the ice sheets contracted. These ice age–interglacial cycles, lasting tens of thousands of years in Figure 2.12c, occur during icehouse periods (Figure 2.10); during greenhouse periods, there is little permanent ice anywhere on the planet.

From approximately 2.5 million to 1 million years ago, ice ages occurred every 41,000 years (Figure 2.12c). Then, about 1 million years ago, the frequency of ice ages shifted to every 100,000 years, and the magnitude of the ice-age cycles increased (Figure 2.12d).

Figure 2.13 zooms in again, showing a record of temperature and carbon dioxide levels for the Antarctic region over the past 410,000 years constructed from ice cores. This record

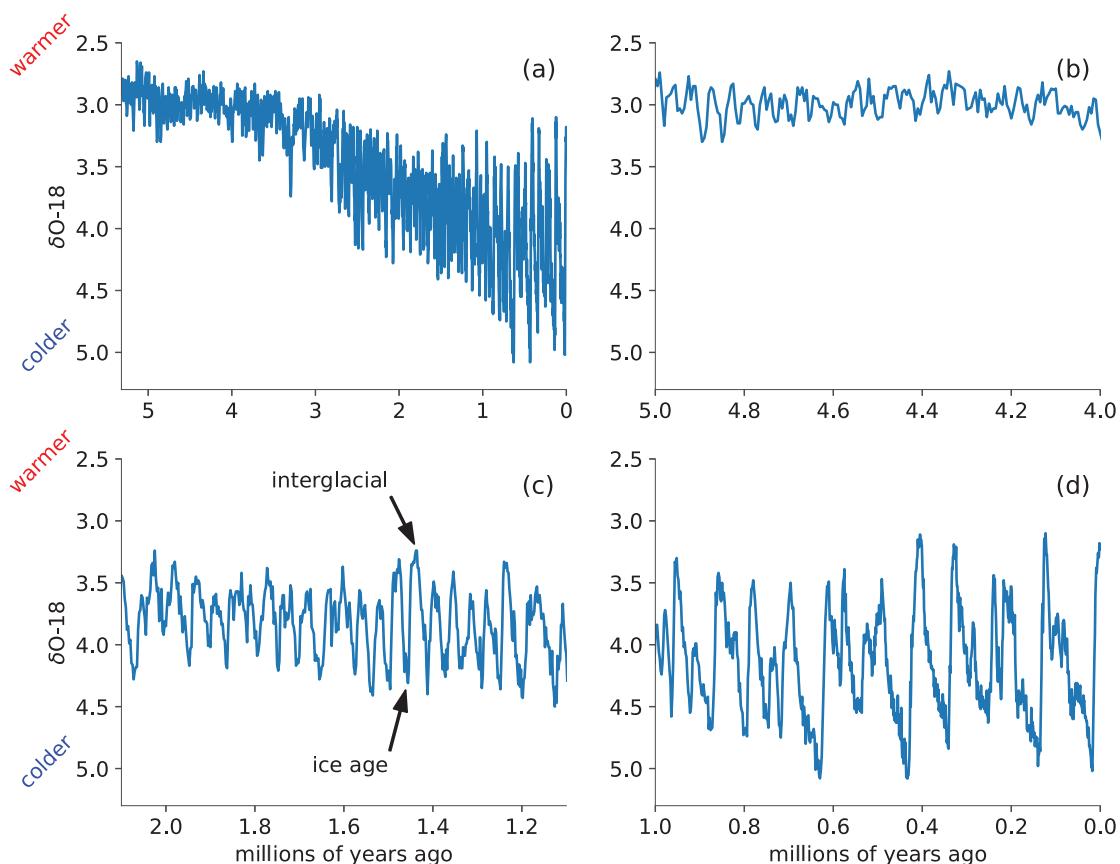


Figure 2.12 Measurement of deep ocean temperature and global ice volume over the past 5.3 million years. The vertical axis measures the relative abundance of oxygen-18, a heavy isotope of oxygen that is a proxy for temperature, in ocean sediment cores. The global average temperature difference between the top and bottom of the graph is roughly 10°C. Data are from Lisiecki and Raymo (2005) (downloaded from <https://lorraine-lisiecki.com/stack.html>, accessed May 29, 2020).

shows in more detail the shape of recent ice-age cycles – the cooling into an ice age is slow, taking several tens of thousands of years, whereas the warming at the end of an ice age occurs faster, in approximately 10,000 years. Overall, these ice ages lasted about 100,000 years, while the interglacials are relatively short, lasting 10,000 to 30,000 years.

The coldest period during an ice age, known as glacial maximum, occurs right before the end of the ice age. The *last glacial maximum* occurred about 20,000 years ago, when the global average temperature was about 6°C cooler than modern temperatures. The last ice age ended about 12,000 years ago, and since then we have been enjoying a rather pleasant interglacial.

You might also notice in Figure 2.13 that atmospheric carbon dioxide, which can also be estimated from the ice core, varies closely with atmospheric temperature over these ice-age

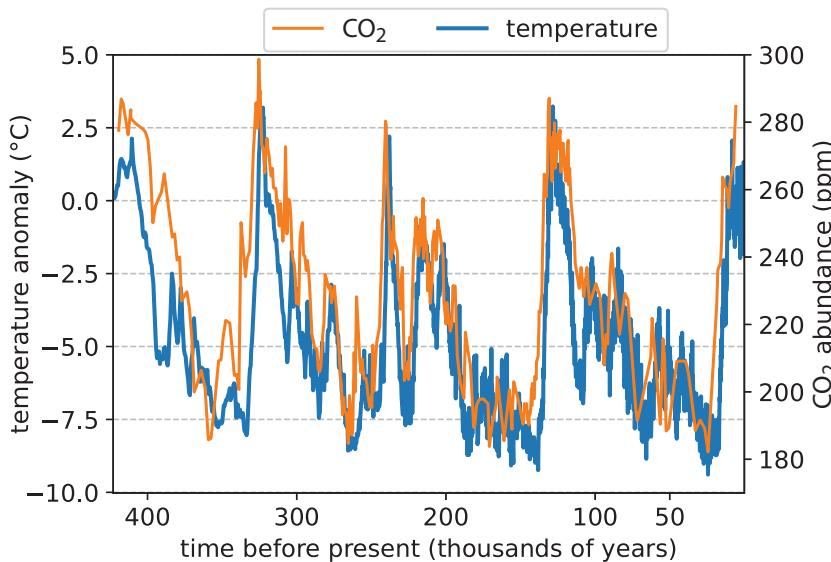


Figure 2.13 Temperature anomaly of the southern polar region (blue line) over the past 410,000 years, relative to today's temperature, constructed from an Antarctic ice core. Carbon dioxide (orange line) is from air bubbles trapped in the ice (data from Petit et al. (2000); downloaded from https://cdiac.ess-dive.lbl.gov/climate/paleo/paleo_table.html, accessed September 29, 2020).

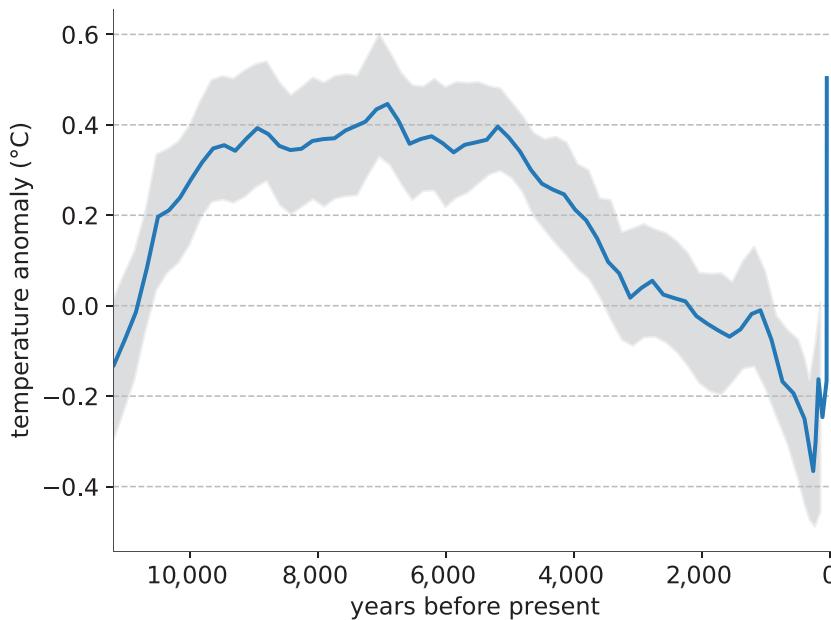


Figure 2.14 Global temperature anomaly ($^{\circ}\text{C}$) of the last 11,000 years, based on multiple proxy records. The shaded region represents the uncertainty in the estimate. Anomalies are calculated relative to the 1961–1990 average. Adapted from Figure 1B of Marcott et al. (2013).

cycles. I will discuss the implications of this relationship in detail in Chapter 7, but you would be correct if you concluded that carbon dioxide variations play a key role in the generation of the ice-age cycles.

Figure 2.14 zooms in again to show the global temperature of *the Holocene*, the period beginning at the end of the last ice age, about 11,700 years ago. This estimate shows that

temperatures peaked about 7,000 years ago and then started a slow, long-term decline that bottomed out in a period 200 to 300 years ago, known as the *Little Ice Age*, during which temperatures were about 1°C below today's. After the Little Ice Age, temperatures began warming. Today's temperatures are comparable to peak temperatures of the mid-Holocene.

Aside 2.2: What does the paleorecord tell us about how serious of a threat climate change is?

As we will talk about in Chapter 8, forecasts for the twenty-first century are for a few degrees Celsius of warming. That might not seem like much, but the paleorecord says otherwise. The ice ages were only about 6°C colder than today, and that temperature difference was enough to turn the Earth into essentially a different planet. Glaciers several thousand feet thick covered much of North America, sea level was 100 m lower than today, and there were significant accompanying changes in the world's environment and ecosystems.

The Little Ice Age was about 1°C below today's temperature, a seemingly trivial amount, but the climate was different enough that we call it the Little Ice Age. Glaciers in Europe advanced dramatically, destroying numerous farms and villages. Paintings from the time show a cold and snowy climate that does not exist today. In London, the freezing of the Thames River, commonplace during the era, was celebrated with a winter fair that took place on the frozen river – that river no longer freezes over. In their camp in Valley Forge, PA, the Continental Army nearly froze to death during the winter of 1777–1778.

Thus, we should expect warming of a few degrees Celsius, if it comes to pass, to radically change the planet we're living on. We will discuss this in more detail in Chapter 9.

Figure 2.15 zooms in one last time to show global average temperature over the past 2,000 years. Temperatures generally declined over this period, until the 1800s. At that point, we see a dramatic warming that clearly deviates from the previous 1800 years.

This vast and growing body of information about the Earth's past allows us to reach several important conclusions. First, the Earth has been both much warmer than today and much colder. Looking at the more recent past (the Holocene), we see that temperatures have been declining for about 7,000 years, until around 1800, at which time temperatures began rapidly increasing. We'll see later in the book that is no mere coincidence – it is exactly when humans started adding greenhouse gases to the atmosphere.

Human society, made up of mega-cities and concrete and iron infrastructure on a global scale, has only been around for a century or two. This means that the range of global average temperatures our society has experienced is small, around 1°C. As our climate continues to warm, we are departing from conditions under which human society developed and thrived. More troubling, the warming we are experiencing is extraordinarily rapid. For example, the

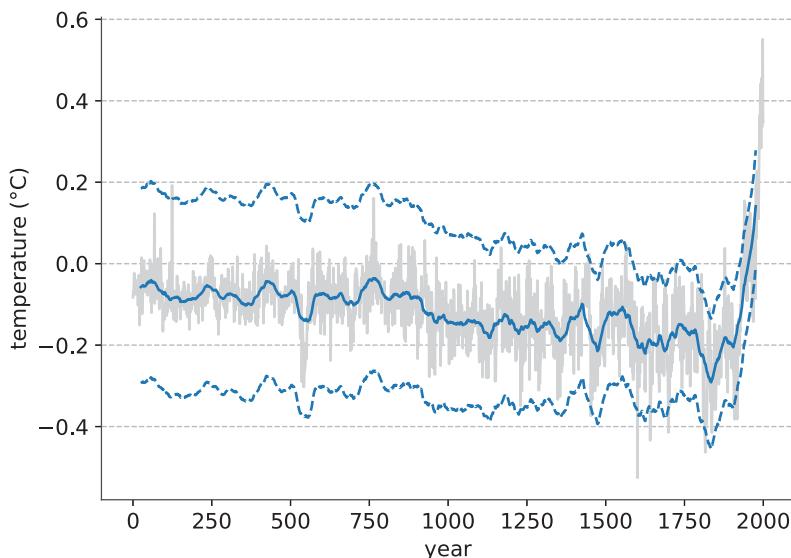


Figure 2.15 Global average temperature anomaly between years 0 AD to 2000 AD. Gray line shows the annual average values, while the blue line shows 50-year smoothed values. The dashed blue lines show the 10–90 percent confidence interval of the smoothed value. Anomalies are calculated relative to the 1951–1980 average. Data are ensemble-average 2-m air temperature (that is, temperature 2 m above ground) from the Last Millennium Reanalysis of Tardif et al. (2019), version 2.1 (downloaded from <https://atmos.washington.edu/~hakim/lmr/LMRv2/index.html>, accessed April 30, 2021).

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). Even if you know nothing else about climate change, this by itself should compel your attention.

The challenge for the scientific community is to come up with a theory that explains all of the variations in the climate record, from snowball Earth 700 million years ago to the rapid warming of the last century. In the next few chapters, we will learn about the fundamental physics that governs our climate, and then, in Chapter 7, we will put it all together to show that most of the modern warming can be attributed to human activity.

2.4 Chapter Summary

- The most well-studied and reliable source of temperature data for the past century is the surface thermometer network. It shows a global and annual average warming of 1.1°C between the late 19th century and the 2010s.
- Scientists have a large number of independent measurements with which to confirm the warming seen by the surface thermometer network. These include satellite measurements

of temperature, measurements of the amount of ice on the planet, ocean heat measurements, and sea-level measurements. All of these data confirm the warming seen in the surface thermometer data.

- Because of the overwhelming evidence supporting it, the scientific community has concluded that the observed warming of the climate system is beyond doubt – the IPCC uses the word “unequivocal.”
- Looking back further in time, we see that the Earth’s climate has varied widely over its 4.5-billion-year history. The geologic record shows that the climate has been both warmer and cooler than today’s climate.
- Over the past few million years, the Earth has oscillated between ice ages and warmer interglacial periods. Ice ages are about 6°C cooler than the interglacials. The Earth is currently in an interglacial.
- We are currently in the Holocene, the period that began at the end of the last ice age. Temperatures peaked about 7,000 years ago and declined until about 200 years ago, after which temperatures began rapidly rising. This abrupt rise coincided with the beginning of society-wide combustion of fossil fuels.

ADDITIONAL RESOURCES

One of the Internet’s great resources for climate information is skepticalscience.com. It has many articles about the science of climate change, including discussions of the quality of the various temperature records. For example, here is a nice article on the reliability of the surface thermometer measurements: www.skepticalscience.com/surface-temperature-measurements.htm. When you are confronted with a claim that sounds wrong (“We’re entering a new ice age!”), this is the first place you should go to check it out.

See www.andrewdessler.com/chapter2 for additional resources for this chapter.

TERMS

Cherry picking
Eocene Climatic Optimum
Greenhouse Earth
Holocene
Ice ages
Icehouse Earth
Interglacials
Last glacial maximum
Little Ice Age

Paleoproxies
Snowball Earth
Temperature anomaly

PROBLEMS

1. Every year, you measure the height of a child relative to a coat hook on the wall. In the first year, he was 2" below the hook, the next year he was 1.5" below the hook, the next year he was 0.75" below the hook, the next year he was even with the hook, the next year he was 0.5" above the hook, and the last year he was 1.5" above the hook.
 - (a) What was the total amount the child grew?
 - (b) What was his average growth rate (in inches per year)?
 - (c) What was his absolute height at the end of the last year?
2. From Figure 2.2, how much did the Earth warm between (a) 1880 and 2020 and (b) 1970 and 2020? Provide answers in both degrees Celsius and degrees Fahrenheit.
3. If you found out that the satellite data were unreliable because of a previously unknown error, would that change your opinion about whether the Earth is currently warming? Why or why not?
4. A reporter asks you to explain why scientists are so confident that the Earth has undergone a general warming over the past century. Knowing that reporters hate long answers, construct an answer that takes 60 seconds or less to deliver (that corresponds to less than 100 words).
5. List the evidence that supports the contention that the Earth is currently warming. Is there any evidence that goes against this conclusion?
6. What is a temperature anomaly? Why are temperature anomalies typically used in global temperature calculations?
7. Download the annual and global average temperature data from Berkeley Earth (link to data located at www.andrewdessler.com/data) and reproduce Figure 2.2. Calculate the trend for the past 30 years and for the past 100 years.
8. Download the monthly and global average temperature data from Berkeley Earth (located at www.andrewdessler.com/data). Calculate trends over various lengths of time (ranging from a few years to several decades). If you look at the period after 1970, can you find any periods with negative trends? Over what length of time are the trends mainly positive?
9. Why do we turn to paleoproxy measurements to infer the temperature of millions of years ago?

10. Go to the station page on Berkeley Earth (link to data located at www.andrewdessler.com/data) and find a station near your hometown or city you live in today that covers a century or so (they're normally in the bigger cities). How does the final time series (the "breakpoint adjusted" comparison) differ from the global average time series in Figure 2.2? Should it? The page also shows the adjustments to the raw data. Did the time series require a lot of adjustments?
11. A global warming advocate tells you that the Earth is now warmer than it has ever been. Is that correct?
12. The stations that make up the surface thermometer data set must be individually adjusted to account for known issues in the data set (e.g., station moves). Some skeptics claim that the warming in the record (e.g., Figure 2.2) is due to these adjustments. We can check this. Berkeley Earth provides a "raw" land data set in which no adjustments are made (located at www.andrewdessler.com/data) and this can be compared to the data with adjustments. Download the data sets and compare them. How big of an impact do the adjustments have? Do the skeptics have a point?

3

Radiation and Energy Balance

The Earth's climate is a complex physical system. Nevertheless, we can still understand much about the climate even without an advanced degree in physics. In this chapter, I introduce the important physics required to understand the climate. Then, in Chapter 4, we will use this physics to construct a simple model of our climate.

3.1 Temperature and Energy

Before we get into the physics of climate, it is useful to first talk about the concept of *energy*. To a physicist, energy is the capacity to do work – such as lifting a weight, turning a wheel, or compressing a spring. The unit of energy most frequently used in physics is the *joule*, abbreviated as the letter J. One joule is not a huge amount of energy: It is approximately the amount of energy required to lift 100 g about 1 m – or to lift an apple about 3 ft.

Energy often moves from one place to another. The rate at which energy is flowing is referred to as *power*. It is usually expressed in *watts*, abbreviated as the letter W. One watt is equal to one joule per second – that is, $1\text{ W} = 1\text{ J/s}$ – so a 60-W light bulb consumes 60 J of energy every second. Alternatively, 60 W is the power required to lift 60 apples about 1 m every second.

An analogy may help to illuminate the difference between power and energy. A gallon is a quantity, such as a gallon of water. This is akin to a joule, which is a quantity of energy. The rate at which water flows through a pipe is measured in, say, gallons per minute. The rate at which energy flows is the power, and it is measured in watts (joules per second).

Example 3.1: How much power does it take to run a human body?

A typical human consumes approximately 2,000 food calories per day. Calories are an alternative unit of energy, where 1 food calorie = 4,184 J. Thus, 2,000 food calories correspond to 8,368,000 J. One day has $24\text{ hours} \times 60\text{ minutes} \times 60\text{ seconds} = 86,400\text{ seconds}$ in it, so dividing 8,368,000 J by 86,400 s yields $97\text{ J/s} = 97\text{ W}$. Thus, the typical human requires roughly 100 W to power his or her body – about the same power required to run one or two light bulbs. One horsepower is approximately 740 W, so another way to think about this is that it takes about one-seventh of a horsepower to run your body.

The *internal energy* of an object refers to how fast the atoms and molecules in the object are moving. In a cup of water, for example, if the water molecules are moving slowly, then the water has less internal energy than another cup in which the molecules of water are

moving rapidly. In a solid, the movements of the atoms are approximately fixed in space by intermolecular forces – that is why it is a solid. The atoms, however, can still move small distances around their fixed position. The faster these atoms move about their fixed position, the more internal energy the object has.

This brings us to a concept that most people are familiar with: *temperature*. Temperature is a measure of the internal energy of an object. As an object's internal energy increases and the molecules of the object speed up, the temperature of the object also increases. Thus, if you have two cups of water, one hot and the other cold, you can conclude that the water molecules in the hot cup are moving faster than the water molecules in the cup of cold water.

In Chapter 1, I introduced the Celsius temperature scale, which is used by most people around the world. There is another temperature that is favored by physicists, and it is called the *Kelvin scale*. The temperature in kelvin is equal to the temperature in degrees Celsius plus 273.15 ($K = C + 273.15$). Thus, the freezing temperature, 0°C , is equal to 273.15 K,¹ whereas the boiling temperature, 100°C , is equal to 373.15 K. “Room temperature” is 22°C or so, which is about 295 K. Most temperatures found in the Earth’s atmosphere are between 200 K and 300 K, and the average surface temperature of the Earth (today, at least) is about 288 K.

Physicists prefer the Kelvin scale because temperature expressed in kelvin is proportional to internal energy. Thus, if the temperature doubles from 200 K to 400 K, then the internal energy of the object also doubles. If the internal energy of an object increases by 10 percent, then the temperature expressed in kelvin also increases by 10 percent. And 0 K is absolute zero – the temperature at which molecules have zero internal energy and cease moving; this is the coldest possible temperature. Because of this important quality, the physics equations introduced in this chapter and the next require energy to be expressed in kelvin.

3.2 Electromagnetic Radiation

It has long been recognized that the warmth of our climate is provided by the Sun. However, the Sun sits 150 million kilometers away from the Earth, with the vacuum of space in between. How does energy from the Sun reach the Earth?

Energy is transported from the Sun to the Earth by *electromagnetic radiation*. Electromagnetic radiation includes visible light, like that put out by your desk lamp or the Sun, X-rays, like those that allow us to detect broken bones, microwaves, like those that cook your dinner, and radio-frequency waves, like those that bring calls to your cell phone and WiFi to your computer.

¹ Note that you do not use a degree sign ($^\circ$) when writing temperature in kelvin. Thus, room temperature is 295 K, not 295°K .

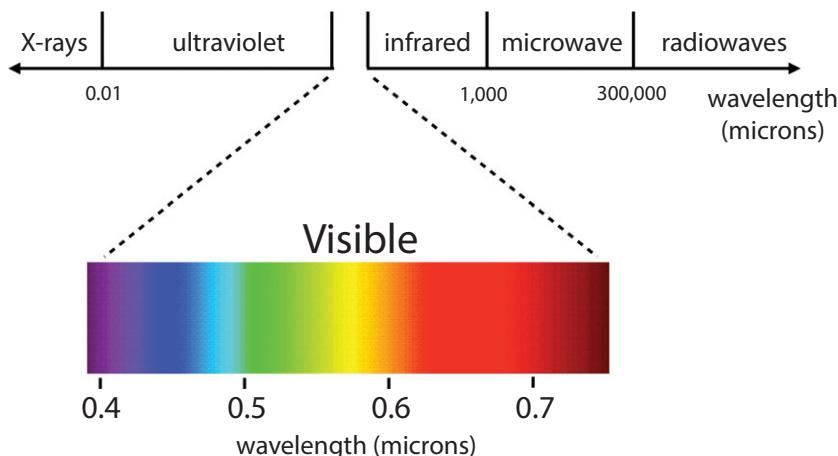


Figure 3.1 The electromagnetic spectrum. Note that the visible part makes up only a minor part of this spectrum.

One can think of electromagnetic radiation as a stream of *photons*, small discrete packages of energy.² As photons travel from Point A to Point B – such as from the Sun to the Earth – each one carries a small amount of energy, and this is how energy is transported from the Sun to the Earth.

Photons have a characteristic size, referred to as the *wavelength*, which determines how the photons interact with the world. Photons with wavelengths of between 0.4 and 0.8 microns (a *micron*, abbreviated as μm , is a millionth of a meter; a human hair is $100\ \mu\text{m}$ or so in diameter) can be seen with the human eye – so we refer to these photons as *visible*. Within the visible range, the different wavelengths appear to the human eye as different colors (Figure 3.1). Humans see photons with wavelengths near $0.4\ \mu\text{m}$ as violet, $0.6\ \mu\text{m}$ as yellow, and $0.8\ \mu\text{m}$ as red.

Photons with longer wavelengths, from 0.8 to $1,000\ \mu\text{m}$, are termed *infrared* – from the Latin for “below red” – because they are beyond the red end of the visible spectrum. Despite being invisible to humans, these photons play an important role in both the Earth’s climate and in our everyday lives. Photons with wavelengths just below the human detection limit of $0.4\ \mu\text{m}$ are called *ultraviolet* because their wavelength is beyond the violet end of the visible spectrum.

Photons with wavelengths between $1,000\ \mu\text{m}$ ($1\ \text{mm}$) and $0.3\ \text{m}$ are termed microwaves, and photons in this wavelength range are used in many familiar applications, from cooking to radar. Wavelengths longer than about $0.3\ \text{m}$ are radio-frequency waves, and they are used, as the name implies, in radio applications. The entire electromagnetic spectrum is diagrammed in Figure 3.1.

The wavelength determines a photon’s physical properties. For example, visible and infrared photons cannot go through walls, but radio-frequency photons can. The human eye can detect visible photons but not infrared or microwave photons. When you get a full body scan

² Electromagnetic radiation also behaves like a wave, but for this problem it is easier to think of it as a particle.

at the airport's security checkpoint, the machine is most likely using microwaves, which go through clothes but are stopped by denser materials such as flesh, a bomb, or a gun. Finally, the atmosphere is transparent to visible photons but less so to infrared photons; this fact has enormous implications for our climate and will be discussed at length in Chapter 4.

3.3 Blackbody Radiation

We know that both the Sun and the lamp on your desk are emitting photons. After all, you can see the visible photons that they are emitting. They are not, however, the only things around you that are emitting photons. In fact, *everything around you* is emitting photons all of the time. So right now, you are emitting photons, as are the walls of the room you are sitting in, your desk, your dog, this book. Everything.

If everything is emitting photons, then why doesn't everything glow like a light bulb? It turns out that the wavelength emitted is determined by the object's temperature. Figure 3.2 plots emissions spectra for idealized objects called blackbodies at three temperatures. An emissions spectrum shows the power carried away from an object by photons at each wavelength.

Figure 3.2a shows the distribution of photons emitted by a 300-K blackbody, about room temperature. Photons emitted by this object almost exclusively have wavelengths greater than 4 μm or so. These wavelengths are outside the range that is visible to humans (0.4–0.8 μm), so humans cannot see them. This is, in fact, the origin of the term *blackbody*. At room temperature, the object appears black because the photons emitted by these objects are invisible to humans (also playing a role is that blackbodies absorb all photons that fall on them – they do not reflect any). Blackbodies are idealized constructs, but many objects nevertheless behave like one, at least approximately.

Figure 3.2a also shows that the peak of the emissions spectrum for a 300-K blackbody occurs near 10 μm . It turns out that there is a simple relation between an object's temperature and the peak of its emission spectrum. This relation is known as *Wien's displacement law*:

$$\lambda_{\max} = \frac{2,897}{T} \quad (3.1)$$

T is the temperature of the blackbody in kelvin and λ_{\max} is the wavelength of the peak of the emission spectrum in microns. If we put 300 K into Equation 3.1, we get 9.7 μm , which is in good agreement with Figure 3.2a. Note the importance of using Kelvin temperature – had I used the temperature in degrees Celsius, I would have calculated $\lambda_{\max} = 2,897/27 = 107 \mu\text{m}$.

Wien's displacement law also tells us that, as an object heats up, λ_{\max} decreases, shifting the peak of its emission spectrum to shorter wavelengths. Thus, a 1,600-K object has $\lambda_{\max} = 1.8 \mu\text{m}$ and a 6,000-K object has $\lambda_{\max} = 0.5 \mu\text{m}$, values consistent with the emissions spectra in Figures 3.2b and 3.2c.

It is worth emphasizing that objects do not just emit photons at λ_{\max} ; they emit them over a range of wavelengths around λ_{\max} . So, while $\lambda_{\max} = 1.8 \mu\text{m}$ for the 1,600-K object, the

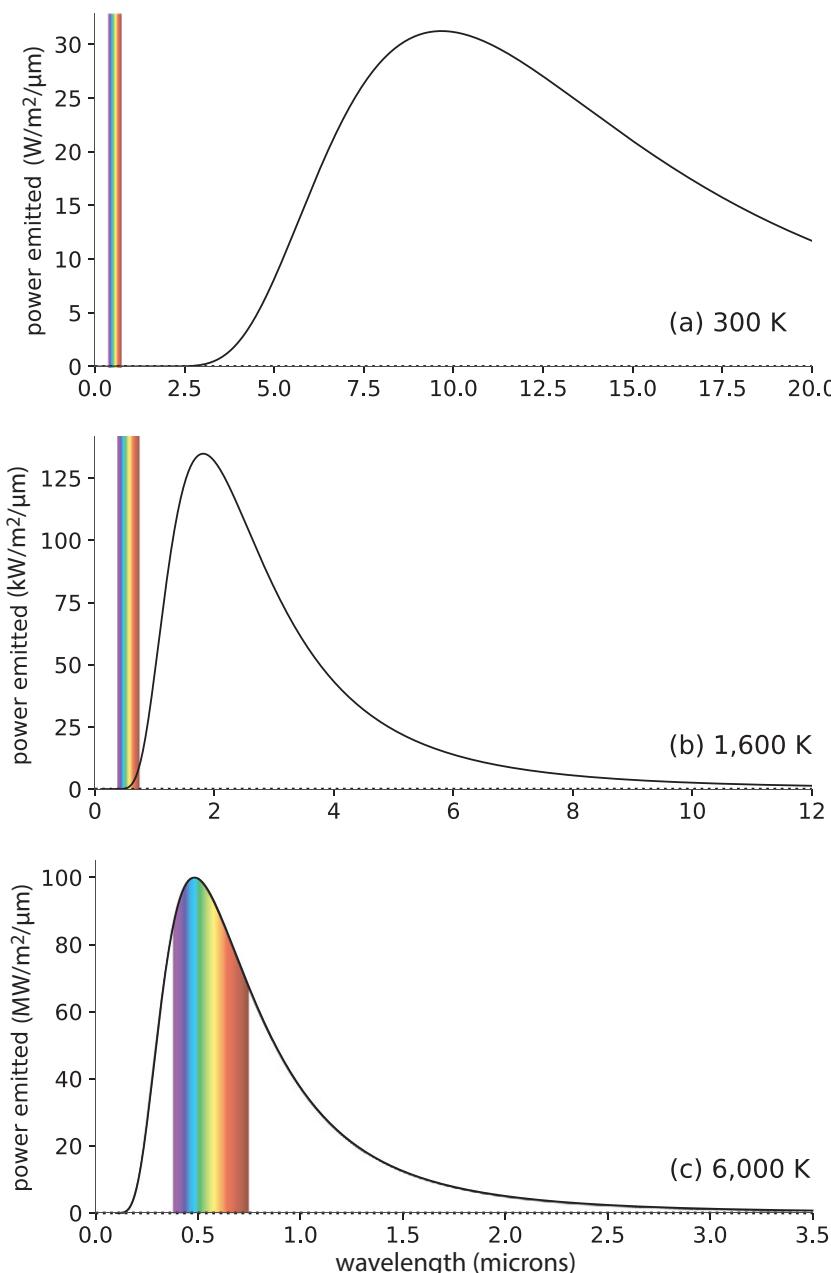


Figure 3.2 Power emitted at different wavelengths from objects at three temperatures: (a) 300 K, (b) 1,600 K, and (c) 6,000 K. The rainbow band on each plot shows the range of wavelengths visible to human eye.

object emits photons over a range of wavelengths from 0.7 to 10 μm . Because a fraction of the photons emitted by this object have wavelengths between 0.7 and 0.8 μm , which lie at the red end of the visible spectrum, humans will perceive a 1,600-K object as having a slight reddish glow. In other words, this object is glowing “red hot.”

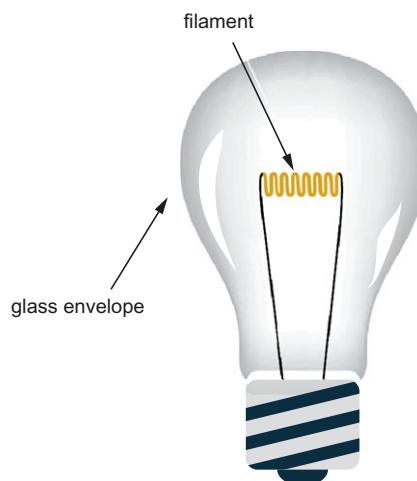
For the 6,000-K object, most of the photons emitted fall within the visible range (Figure 3.2c). Our Sun is, to a good approximation, a 6,000-K blackbody, and the distribution of photons from the Sun is closely approximated by this blackbody spectrum. Because being able to see confers a strong advantage in surviving, it is no surprise that the eyes of humans and other animals have evolved to see this range of wavelengths. In fact, the human eye is maximally sensitive to light with a wavelength near $0.5 \mu\text{m}$, which is the λ_{max} for a 6,000-K blackbody. The chlorophyll molecule, the key component of photosynthesis, strongly absorbs photons in the visible range, showing that plants have also evolved to take advantage of photons emitted by the Sun.

Finally, if the photons emitted by room-temperature objects are not visible to our eyes, how can we see room-temperature objects, such as this page? What you see when you look at a room-temperature object are visible photons (emitted by the Sun or a light bulb or some other hot object) that have bounced off the object. Objects do not reflect all wavelengths equally. When you see a green object (like a leaf), the object has absorbed the red and blue components of light, while reflecting wavelengths that appear to us to be green.

An everyday object that uses a lot of the concepts that we have discussed in this chapter is the humble *incandescent light bulb*. An incandescent light bulb consists of a glass envelope containing a small filament made of a metal, such as tungsten (Figure 3.3). When the light bulb is turned on, electricity flows through the filament, heating it to around 3,000 K.

Figure 3.4 shows the wavelength distribution of photons emitted by a 3,000-K blackbody. As the figure shows, the filament is hot enough that some of the photons emitted are visible – so humans will see the light bulb glowing and you can use it to light your room. However, 85 percent of the photons emitted have wavelengths in the infrared, too long for the human eye to detect. These infrared photons provide no lighting for humans, and so the energy to produce them is essentially wasted. This makes incandescent bulbs inefficient as light sources.

Figure 3.3 A schematic of a typical incandescent light bulb.



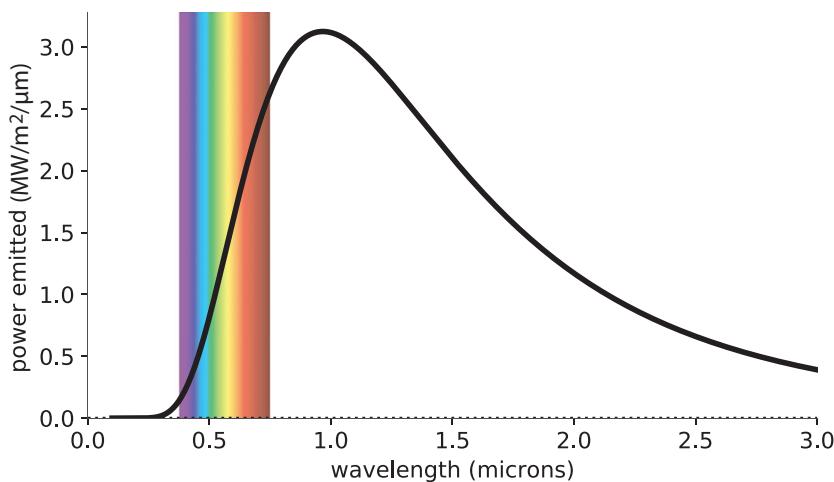


Figure 3.4 Emissions spectrum for a 3,000-K blackbody, a typical filament temperature for an incandescent light bulb, in $\text{MW}/\text{m}^2/\mu\text{m}$.

One way for a light bulb to produce a higher fraction of visible photons is to run the filament at a higher temperature. As described by Equation 3.1, this shifts the distribution of emitted photons to shorter wavelengths, making a greater fraction of them visible to humans – thereby making the bulb more efficient. The optimal temperature for the filament would be about the temperature of our Sun, nearly 6,000 K, which provides the best overlap between blackbody emission and the human visual range. Unfortunately, at such a temperature, the filament would immediately vaporize, and the bulb would be destroyed.

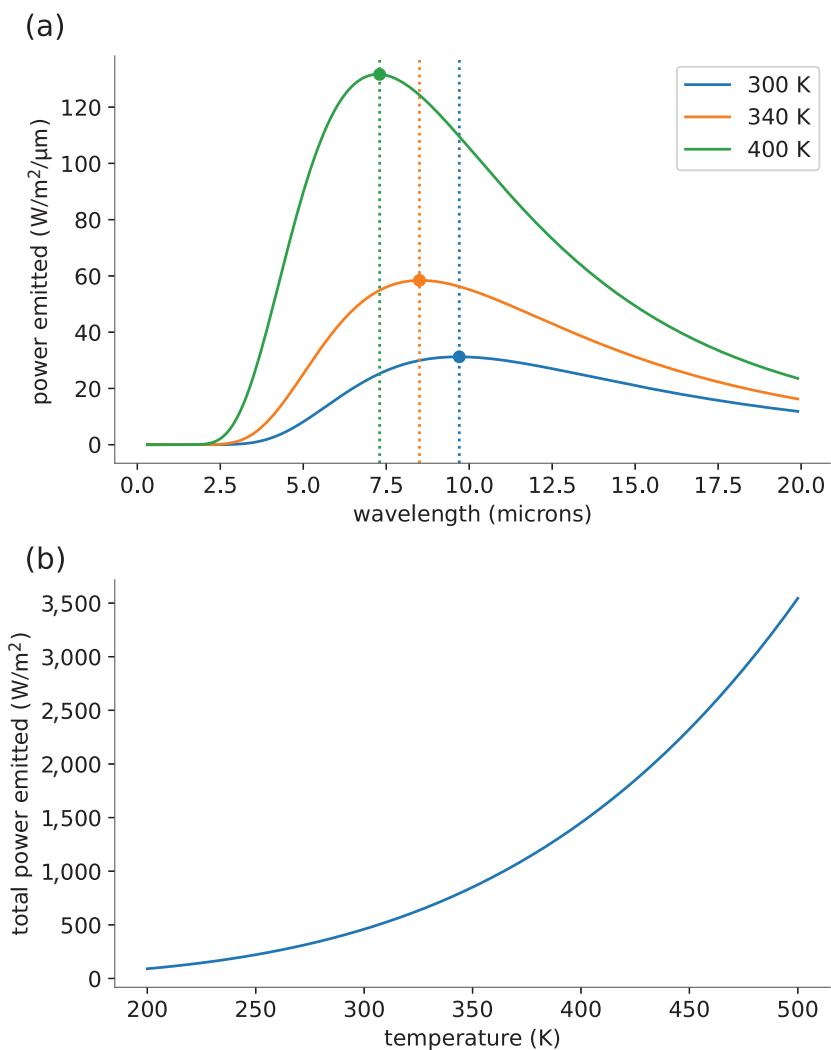
A better way to obtain high-efficiency lighting is to change the technology. Compact fluorescent light bulbs (CFL) and light-emitting diode (LED) light bulbs use different technologies (which I will not discuss here) to emit most of the bulb's photons in the visible wavelength range. The net result is a bulb that is at least five times more efficient. In other words, a 12-W CFL or LED bulb will produce the same amount of visible light as a 60-W incandescent light bulb – and it does this by reducing the amount of infrared light emitted. Because of this, each high-efficiency light bulb you use will save you around ten dollars a year in electricity.

Not only does the wavelength of emission change with temperature, but the total power emitted by a blackbody also increases with temperature. This is shown in Figure 3.5a, which shows three different blackbody-emission curves on a single plot. The plot shows that, at every wavelength, warmer objects emit more power than cooler objects.

For a different view of this, Figure 3.5b plots the total power emitted by a blackbody as a function of temperature (this is calculated by summing the emissions over all wavelengths). It also shows that the power emitted increases with temperature. It turns out that there is a simple relation, known as the Stefan–Boltzmann equation, between the total power radiated by a blackbody and temperature:

$$P/a = \sigma T^4 \quad (3.2)$$

Figure 3.5 Plots of (a) the distribution of power emitted by a blackbody at three different temperatures (300, 340, and 400 K), in $\text{W/m}^2/\mu\text{m}$, and (b) total power emitted by a blackbody as a function of temperature, in W/m^2 .



P/a is the power emitted by a blackbody per unit of surface area, with units of watts per square meter; σ is the Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4$; and T is the temperature of the object in kelvin. If you multiply P/a by the surface area a of the object (in square meters), then you get the total power emitted by a blackbody, in watts.

The Stefan–Boltzmann equation has wide applications. By measuring the amount of power emitted by an object, astronomers use it to infer the temperature of distant stars and planets. The US military uses the equation to build sensors to identify and lock onto hot jet engines against a cold sky in the guidance systems of heat-seeking missiles. And the ear thermometer that might be in your medicine cabinet right now uses this same physics to convert the infrared emission from the eardrum and surrounding tissue into an estimate of body temperature.

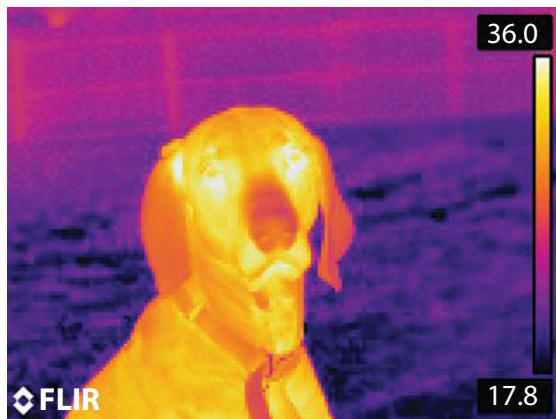


Figure 3.6 Photo of Kasper Dessler (2005–2016) in the infrared, with colors assigned to different temperatures.

As a further example, Figure 3.6 shows an image of my dog, Kasper, in the infrared. To construct this image, the temperature of each pixel is estimated from a measurement of the infrared emission from that pixel. Bright colors indicate warm temperatures and dark colors indicate cool temperatures. Like humans, dogs are mammals, and their body temperature is around 38°C. Fur is an insulator, however, so fur-covered regions of the dog tend to be cooler. Areas that are not fur-covered, such as the eyes, are close to the dog's internal temperature. Note also Kasper's cold nose.

Example 3.2: How fast is a room-temperature basketball losing energy by the emission of photons?

At room temperature, a blackbody is emitting $\sigma(300\text{ K})^4 = 460\text{ W/m}^2$. A basketball with a radius of 5 in. = 0.13 m has a surface area of $4\pi(0.13\text{ m})^2 = 0.2\text{ m}^2$. The total rate of energy loss from a room-temperature basketball as a result of blackbody photon emission is therefore $460\text{ W/m}^2 \times 0.2\text{ m}^2$, or 92 W. This is about the same emitted power as a typical light bulb. Of course, you cannot light a room with a room-temperature basketball because the photons emitted by it are outside the range that humans can see.

3.4 Energy Balance

One of the cornerstones of modern physics is the first law of thermodynamics, which states that energy is conserved. Because photons are just little packets of energy, the first law tells us that when an object emits a photon, the emitting object's internal energy must decrease. And because temperature is a measure of internal energy, the emission of a photon therefore causes the object to cool. Similarly, if a photon hits an object and is absorbed, then the energy of the photon is transferred to the object's internal energy, and the object warms.

Table 3.1 Energy balance summary

Condition	Effect on internal energy	Effect on temperature
If $E_{\text{in}} > E_{\text{out}}$ for an object	Internal energy of that object increases	Temperature of that object increases
If $E_{\text{out}} > E_{\text{in}}$ for an object	Internal energy of that object decreases	Temperature of that object decreases
E_{in} equals E_{out} for an object	Internal energy of that object is not changing	Temperature of that object is not changing

Objects are always absorbing and emitting photons – in fact, you’re doing it right now. The net change in internal energy of an object is the amount of *energy in* (E_{in}) from absorbing photons minus the *energy out* (E_{out}) from emitting photons. If *energy in* for an object exceeds *energy out*, then the internal energy of the object increases and so does its temperature. If, on the other hand, *energy out* for an object exceeds *energy in*, then the internal energy and temperature decrease. If *energy in* and *energy out* are equal, then the internal energy and temperature are unchanging, a situation we call *equilibrium*. These cases are summarized in Table 3.1.

Money is also conserved, making balancing your checkbook a good analogy for energy balance. Funds, such as your paycheck or a birthday check from your grandmother, are periodically deposited into the account. At the same time, funds are withdrawn, to pay for things such as food, rent, or your cell phone bill. The change in your bank balance is equal to the difference between the total deposits (*money in*) and total withdrawals (*money out*). In equation form, we write this as follows:

$$\text{Change in balance} = \text{money in} - \text{money out}$$

If *money in* exceeds *money out*, that is, your deposits exceed your withdrawals, then the change in balance is positive and your balance increases. If *money out* exceeds *money in*, then the change in balance is negative and your balance decreases. If *money in* and *money out* are equal, the change in balance is zero and your balance is unchanged.

Another good example that draws many of the concepts in this chapter together is your home oven. Most people, if asked how an oven cooks, would answer, “Because it’s hot inside.” However, you may be surprised that the physics is subtler than you realize. Ovens do not cook because the air in the oven is hot – air is a terrible conductor of heat. Rather, ovens cook by infrared radiation.

When an electric oven is turned on, electricity runs through a heating element. The element heats up, eventually reaching temperatures high enough that it glows a reddish orange. At this point, the element is radiating an enormous amount of power, typically thousands of watts.

The photons emitted by the heating element are absorbed by the walls of the oven, heating them. When the walls reach a predetermined temperature, typically 300–450°F (420–500 K), then the oven is “preheated” and the cook puts the food, say a turkey, into the oven. Let us

assume the turkey came out of the refrigerator and has a temperature of 3°C or 276 K. At this temperature, the turkey is radiating 330 W/m^2 . If the turkey has a surface area of 0.1 m^2 , then the total power radiated by the turkey is 33 W (this is E_{out}).

The turkey is also absorbing photons from the oven's hot walls. The oven walls – let's assume they have a temperature of 375°F (465 K) – are radiating $2,650 \text{ W/m}^2$. The total surface area of the oven's six walls is approximately 1.3 m^2 , so the total power radiated by the oven's wall is roughly 3,500 W. Most of the energy radiated by the oven's walls misses the turkey in the middle and hits the other walls, and only a fraction of photons emitted by the walls hits the turkey. It turns out that the turkey absorbs photons emitted by an area of the walls equal to the surface area of the turkey, 0.1 m^2 . Given that the walls emit $2,650 \text{ W/m}^2$, that means that the turkey is absorbing 265 W of power (this is E_{in}).

Because the turkey is emitting 33 W but absorbing 265 W, then $E_{\text{in}} > E_{\text{out}}$, the internal energy of the turkey is increasing, and it is therefore warming — this is what we mean when we say the turkey is cooking. After a few hours, the turkey reaches the temperature when it is considered “done,” and the cook removes it from the oven.

While the turkey is absorbing energy from the walls, by conservation of energy the walls must be losing energy and cooling down. The oven has a thermostat in it that senses this cooling and turns on the heating element to maintain the wall temperature at 375°F. This occasional cycling back on of the heating element is familiar to any cook.

I hope that you have a sense of the importance of the physics we have discussed in this chapter – it has a profound impact on your life and the world around you. I will show you in the next chapter that it also plays a key role in climate.

3.5 Chapter Summary

- Energy is expressed in units of joules (J). Power is the rate that energy is flowing, and it is expressed in watts (W); $1 \text{ W} = 1 \text{ J/s}$.
- Temperature is a measure of the internal energy of an object and is frequently expressed by physicists using the Kelvin scale. The temperature in kelvin is equal to the temperature in degrees Celsius plus 273.15.
- Photons are small discrete packets of energy. They have a characteristic size, known as the wavelength, which determines how the photons interact with matter. Photons with wavelengths between 0.4 and 0.8 μm are visible to humans; photons with wavelengths between 0.8 and 1,000 μm are called infrared.
- Objects emit blackbody radiation with a characteristic wavelength determined by Wien's displacement law: $\lambda_{\text{max}} = 2,897/T$ (where wavelength is in microns and temperature is in kelvin). Photons emitted by room-temperature objects (around 300 K) are in the infrared and are not visible to humans.
- The relation between temperature and total power emitted by a blackbody is the Stefan–Boltzmann equation: $P/a = \sigma T^4$, where P/a is the power per unit area, $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4$ and T is the temperature in kelvin.

- When a photon is emitted by an object and then absorbed by another object, energy is transferred from the emitter to the absorber.
- If the energy received by an object by absorbing photons exceeds the energy lost by emitting photons, then the object's internal energy increases – and its temperature increases. The object cools off if the energy of emitted photons exceeds the energy received by absorbing photons. When energy gained and lost are equal, the object's temperature does not change, a situation we refer to as equilibrium.

See www.andrewdessler.com/chapter3 for additional resources for the chapter.

TERMS

Blackbody
Electromagnetic radiation
Energy
Equilibrium
Incandescent light bulb
Infrared radiation
Internal energy
Joule
Kelvin scale
Micron
Photons
Power
Temperature
Ultraviolet
Visible photons
Watt
Wavelength
Wien's displacement law

PROBLEMS

1. The temperature of an object increases by 1 K. How much did it increase in degrees Fahrenheit and how much in degrees Celsius?
2. A sphere with a radius of 1 m has a temperature of 100°C. How much power is it radiating?
3. As a room-temperature object increases in temperature, it begins to glow. Describe the progression in colors as the object heats up. Ultimately, what happens to the glow if the warming continues to nearly infinite temperatures?
4. Consider two stars that have the spectra shown in Figure 3.7. Based just on the information provided in this plot, what are the colors and radiating temperatures of the stars?

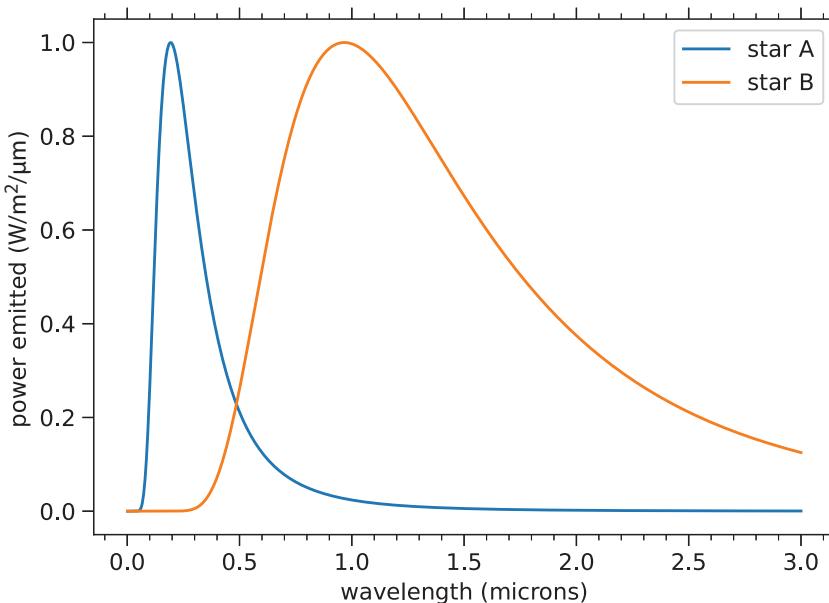


Figure 3.7 Emissions spectra of two hypothetical stars.

5. How much total energy (in watts) is the Sun radiating? It is a 6,000-K blackbody with a radius of 700,000 km.
6. You can dim an incandescent bulb by decreasing the temperature of the filament. What do you think happens to the color of the bulb as it dims? Find a dimmer and test your hypothesis.
7. If you run a 60-W light bulb for one week, how many joules of energy have been consumed?
8. Why are incandescent light bulbs being phased out in many countries (including the United States)?
9. The Sun as a blackbody:
 - (a) The Sun is a 6,000-K blackbody. At what characteristic wavelength does it radiate?
 - (b) How much power per unit surface area is the Sun radiating?
 - (c) Imagine that the Sun had a radius twice as large as it does at present, but the Sun emitted the same total amount of energy. What temperature would the Sun have to be?
10. E_{in} is the energy being absorbed by an object, and E_{out} is the energy being radiated.
 - (a) If the temperature of an object is not changing, what does this tell us about E_{in} and E_{out} ?
 - (b) If the temperature of an object is increasing, what does this tell us about E_{in} and E_{out} ?
11. Your bank account has the same balance on April 1 as it did on March 1. Your friend suggests that this means that you did not deposit or withdraw any money for the entire month. Is that correct? Explain why or why not.

12. Heat capacity is the amount of energy you need to add to an object to warm it up by 1 K. The heat capacity of water is 4.18 J/g/K; in other words, if you add 4.18 J to 1 g of water, the water will warm by 1 K. Imagine you have a cup containing 200 g of water that is absorbing 150 W of power. Check your answers by making sure the units work out.

- At what rate is the water warming? Answer in kelvin per second.
- If the cup starts at room temperature, use the answer to part (a) to estimate how long would you have to heat it to reach boiling.
- As the cup heats up, it will radiate more energy to the room. Estimate how much energy the cup is emitting when it reaches the boiling point. You'll have to estimate some quantities yourself to do this.
- Would including enhanced radiation to the room make the water boil faster or will it take longer to boil than was estimated in part (b)?

13. Microwave ovens are able to deliver more energy to food during cooking than conventional ovens, so microwave ovens can cook food faster. For the following, imagine you are cooking a turkey in a conventional oven at 325°F.

- What would you have to do in order to increase the amount of power being delivered to the turkey with the conventional oven?
- Would this cook the turkey faster? Why do we not cook turkeys that way?
- Why are microwave ovens able to deliver so much energy to food, while conventional ovens cannot?
(to answer parts (b) and (c), you have to know that the energy from a photon is absorbed by an object over a layer about one wavelength thick)

14. Refrigerators are essentially reverse ovens – they cool things by maintaining the walls at low temperatures. Imagine you put a turkey with a temperature of 80°C into a refrigerator with walls of 3°C.

- How fast is the turkey losing energy? The answer should be in watts. Assume the turkey has a surface area of 0.1 m².
- Make a (very rough) estimate of how long it will take for the turkey to cool down to the temperature of the refrigerator. To do this, you'll need to know the heat capacity of the turkey, i.e., how many joules need to be removed to cool it by 1 K: 30 kJ/K. Do you think this is a good estimate?

4

A Simple Climate Model

The three most momentous words for the future of the entire human project could well be ‘absorbs infrared photons.’

— Dr. Peter Kalmus¹

Scientists have been studying the Earth’s climate for nearly 200 years and, over that time, a sophisticated and well-validated theory of our climate has emerged. In this chapter, we take the fundamental physics we learned in the last chapter and use it to explain how greenhouse gases warm the planet and why the temperature of the Earth is what it is. By the end of the chapter, you will understand why scientists have such high confidence that adding greenhouse gases to the atmosphere will warm the planet.

4.1 The Source of Energy for Our Climate System

Understanding the climate requires us to do an energy budget calculation, which means that we need to calculate *energy in* and *energy out* for the Earth. The ultimate source of energy for our planet is the Sun, which puts out an amazing 3.8×10^{26} W (380 trillion trillion watts) of power. It emits photons in all directions, so only a small fraction of this energy falls on the Earth.

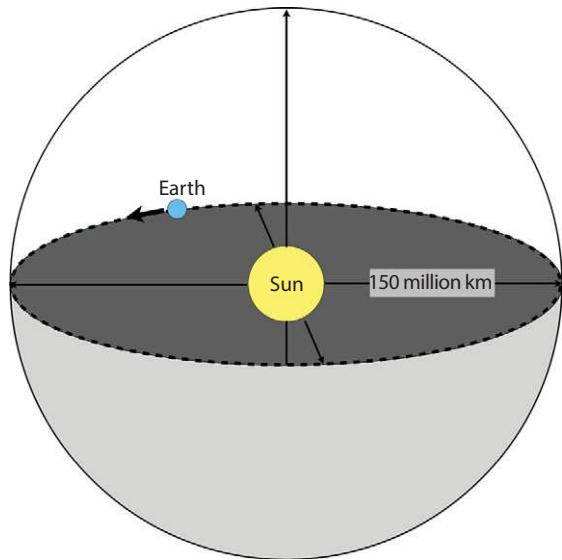
The first step in calculating *energy in* is to determine the intensity of sunlight at the Earth’s orbit. To estimate this, imagine a sphere surrounding the Sun, with a radius equal to the distance from the Sun to Earth, 150 million kilometers (Figure 4.1). Because the sphere completely encloses the Sun, all of the sunlight emitted by the Sun must fall on the interior of the sphere. The surface area of the sphere is $4\pi r^2 = 4\pi(150 \text{ million km})^2 = 2.8 \times 10^{17} \text{ km}^2 = 2.8 \times 10^{23} \text{ m}^2$. Dividing the total energy emitted by the Sun by the area of the sphere produces an estimate of the intensity of solar radiation at the Earth’s orbit: $3.8 \times 10^{26} \text{ W} / 2.8 \times 10^{23} \text{ m}^2 = 1,360 \text{ W/m}^2$. This value, $1,360 \text{ W/m}^2$, is known as the *solar constant* for the Earth; it is frequently represented in equations by the symbol S .

As should be obvious, the solar constant is not actually a constant – it is a function of how far the planet is from the Sun. As a planet gets closer to the Sun, the solar constant increases; if it gets further away, the solar constant decreases. Our next-door neighbor Venus is located

¹ <https://twitter.com/ClimateHuman/status/1261903465028050945>, viewed October 3, 2020.

Figure 4.1 Solar constant calculation:

A hypothetical sphere (gray) surrounding the Sun has a radius equal to the Earth's orbit (dashed line); all radiation emitted by the Sun (black arrows) falls on this sphere.



107 million kilometers from the Sun. Thus, the solar constant for Venus is $3.8 \times 10^{26} \text{ W}$ divided by the surface area of a sphere with a radius of 107 million kilometers, $1.43 \times 10^{23} \text{ m}^2$, which yields a value of $2,600 \text{ W/m}^2$.

Now that we know the Earth's solar constant, we can determine the total solar energy falling on the Earth. The easiest way to quantitatively calculate this is to realize that, if we set up a screen behind the Earth, the Earth would cast a circular shadow on the screen, with a radius equal to the radius of the Earth (Figure 4.2). The amount of sunlight falling on the Earth is equal to the amount that would have fallen into the shadow area if the Earth were not there. The shadow is a circle of radius R , the radius of the Earth, so the shadow area is πR^2 . The total solar energy that would have fallen onto the Earth is therefore πR^2 times the solar constant S .

Given that the radius of the Earth is approximately $6,400 \text{ km} = 6.4 \times 10^6 \text{ m}$, and $S = 1,360 \text{ W/m}^2$, solar energy is falling on the Earth at a rate of $1.75 \times 10^{17} \text{ W}$ or 175,000 TW (1 TW, called a terawatt, is 10^{12} or a trillion watts). This is an immense amount of power. Human society today consumes less than 20 TW, so this simple calculation shows why solar energy is the Holy Grail of renewable energy: We could satisfy all of the world's current energy needs by capturing just 0.01 percent of the solar energy falling on the Earth.

Not all of the photons from the Sun that fall on the Earth are absorbed by it. Some photons are reflected back to space by clouds, ice, and other reflective elements of the Earth system. The reflectivity of a planet is called the *albedo*, from the Latin word for “whiteness” (the word *albino* derives from the same root). It is frequently represented by the symbol α , which is the fraction of incident photons that are reflected back to space; for the Earth, α is

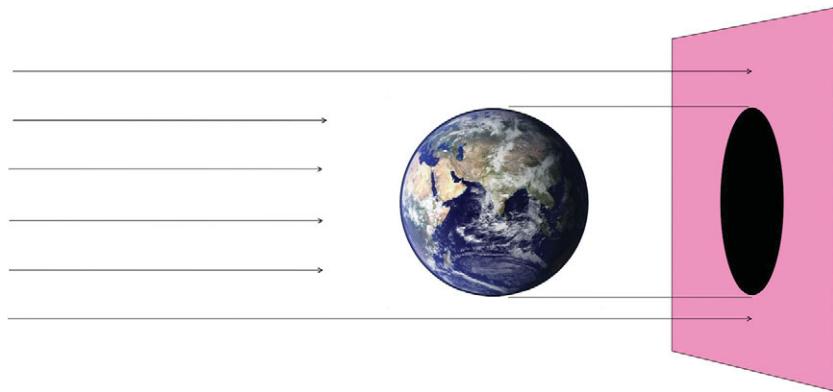


Figure 4.2 The Earth is casting a shadow on a screen placed right behind it because it blocks sunlight. The total amount of solar energy falling on the Earth is the same as what would have fallen into the shadow area. Photo of the Earth from Visible Earth, part of the EOS Project Science Office at NASA Goddard Space Flight Center: <https://visibleearth.nasa.gov/images/57723/the-blue-marble/577271>.

0.3. This means that $1-\alpha$ is the fraction of photons that are absorbed by the Earth. Taking this into account, *energy in* (E_{in}) for the Earth is

$$E_{\text{in}} = S(1 - \alpha)\pi R^2 \quad (4.1)$$

Evaluating Equation 4.1 yields an estimate of E_{in} for the Earth of 123,000 TW. In the rest of the chapter, we will find it more convenient to do the calculation per square meter of the Earth's surface area, so we divide Equation 4.1 by the surface area of the Earth, $4\pi R^2$:

$$\frac{E_{\text{in}}}{\text{area}} = \frac{S(1 - \alpha)\pi R^2}{4\pi R^2} = \frac{S(1 - \alpha)}{4} \quad (4.2)$$

Note that the πR^2 terms cancel, so the net amount of solar energy absorbed per square meter is *not* a function of the Earth's size. Plugging values of $S = 1,360 \text{ W/m}^2$ and $\alpha = 0.3$ into Equation 4.2, we obtain a value of 238 W/m^2 for the Earth's E_{in} . This is a good number to remember.

You might have noticed that I have become a bit sloppy with the terms *energy* and *power* in the previous discussion. In Equation 4.1, for example, the mathematical abbreviation for *energy in* appears on the left-hand side, but the right-hand side has units of power (watts). The physics pedants will argue that we should be writing *power in* instead of *energy in*, and they are indeed correct. However, my choice of terminology here reflects the terminology actually used by scientists who do these kinds of energy-balance calculations. If you go to a meeting of climate scientists or read the peer-reviewed climate literature, you will find that they use *power* and *energy* interchangeably in equations like Equation 4.1 or 4.2. If you worry about things like this, then just keep track of the units and you will always know what is being talked about.

So the Earth absorbs an average of 238 W/m^2 from the Sun, but that does not mean that every square meter of the Earth absorbs this amount. In fact, the availability of solar energy

varies widely across the planet. First, the nighttime half of the Earth receives no energy from the Sun at all. Second, the amount falling on a square meter of the daytime half is determined by the orientation of that square meter with respect to the incoming beams of sunlight. The amount of sunlight received is at maximum if the surface is oriented perpendicular to the incoming beam (Figure 4.3a). As the surface rotates away from perpendicular, the amount of solar energy intercepting the surface decreases (Figure 4.3b), eventually reaching zero for a surface parallel to the incoming beam (Figure 4.3c).

Figure 4.3 Schematic showing how the amount of energy falling on a surface is dependent on the angle between the surface and the incoming beams of light:

- (a) perpendicular,
- (b) rotated away from perpendicular, and
- (c) parallel.

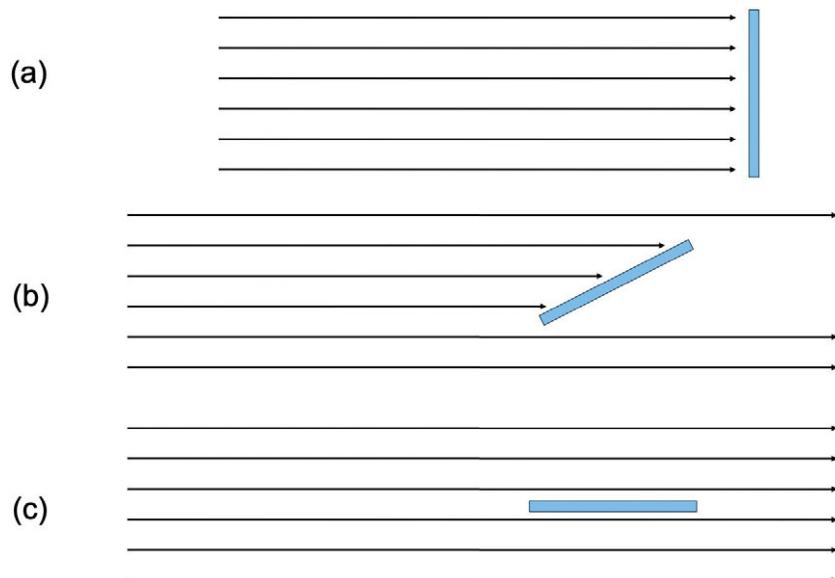


Figure 4.4 Schematic showing how the amount of solar energy falling on a square meter of the Earth's surface is determined by the latitude. Photo of the Earth from Visible Earth, part of the EOS Project Science Office at NASA Goddard Space Flight Center: <https://visibleearth.nasa.gov/images/57723/the-blue-marble/577271>

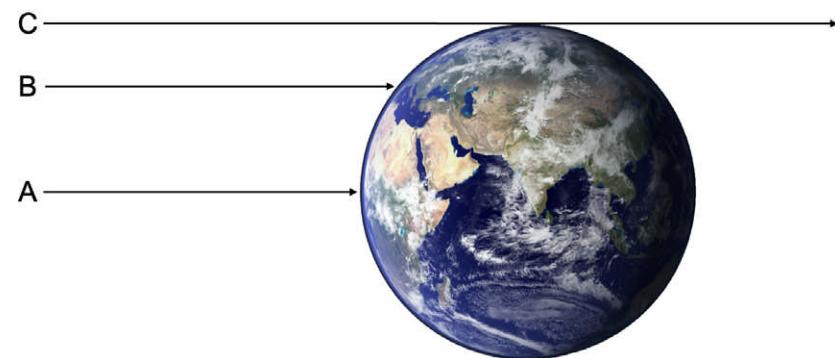


Figure 4.4 shows how this leads to variations in the amount of solar energy falling on the Earth's surface with latitude when averaged over a year. In the tropics (Arrow A), the surface of the Earth is perpendicular to the incoming solar light beams, corresponding to the situation in Figure 4.3a. The surface in the mid-latitudes (Arrow B) is at a moderate angle to the incoming solar light beams, corresponding to the situation in Figure 4.3b. This means that mid-latitudes receive less solar radiation per square meter than the tropics. Finally, the polar regions (Arrow C) correspond to the situation in Figure 4.3c, so little solar energy falls on this region.

In addition to variations in the incoming sunlight with latitude, the albedo of the planet also varies widely. The tropics are mainly ocean, which is dark and therefore has a low albedo. Combined with the large amount of solar energy per square meter, the tropics therefore absorb more solar energy than anywhere else on the planet. The high latitudes, by contrast, are generally covered by snow and ice, giving them a high albedo. Combined with the small amount of solar energy falling on that region, this means that the polar regions absorb the least amount of solar energy. This provides us with a simple qualitative explanation of why the tropics tend to be warm and the polar regions cold.

4.2 Energy Loss to Space

In the early nineteenth century, Joseph Fourier, one of history's great mathematicians, asked a deceptively simple question: Because energy is always falling on the Earth from the Sun, why does the Earth not heat up until it is the same temperature as the Sun? The answer he determined is that the Earth is losing energy at a rate equal to the rate at which it is receiving energy from the Sun.

On the basis of what we learned in Chapter 3, you may rightly guess that the Earth loses energy back to space by means of blackbody radiation. Using the Stefan–Boltzmann equation from Chapter 3, $E_{\text{out}} = P/a = \sigma T^4$, where P/a is the power emitted per square meter, T is the temperature of the planet in kelvin, and σ is the Stefan–Boltzmann constant. Setting E_{in} (Equation 4.2) equal to E_{out} , we get the following equation:

$$\frac{S(1 - \alpha)}{4} = \sigma T^4 \quad (4.3a)$$

Solving for T , we get

$$T = \sqrt[4]{\frac{S(1 - \alpha)}{4\sigma}} \quad (4.3b)$$

Plugging $S = 1,360 \text{ W/m}^2$ and $\alpha = 0.3$ into Equation 4.3b yields² a temperature $T = 255 \text{ K}$ (-18°C). The actual average temperature of the Earth is closer to 288 K (15°C), so our estimate of the Earth's temperature is too cold by 33°C . Where did our calculation go

² The mathematical equation $a = \sqrt[4]{y}$ means that $a^4 = y$. To calculate the fourth root of y on a calculator, you can use the y^x key found on most calculators, where $x = 0.25$. A simpler way to calculate the fourth root of y is to take the square root of y and then take the square root of that number – in other words, $a = \sqrt{\sqrt{y}}$.

wrong? It turns out that what we have neglected is the heating of the planet by the Earth's atmosphere, which is frequently referred to as the *greenhouse effect*.

4.3 The Greenhouse Effect

4.3.1 One-layer Model

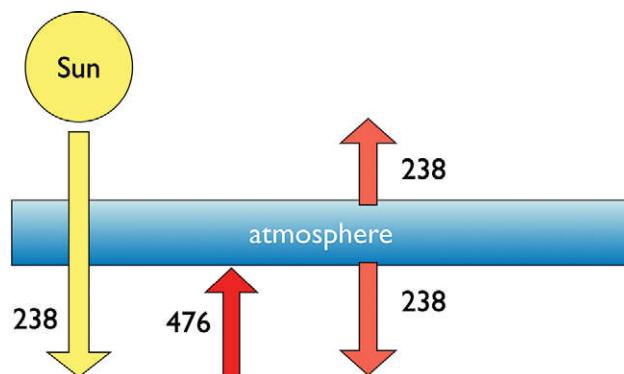
To understand the impact of the atmosphere on our planet's temperature, let us make the following reasonable assumptions:

1. The Earth's atmosphere is transparent to visible photons emitted by the Sun (which mostly have wavelengths from 0.4–0.8 μm), so these photons pass through the atmosphere and are absorbed by the surface.
2. The atmosphere is opaque to infrared photons (wavelengths longer than 4 μm), and all of these photons are absorbed by the atmosphere.
3. The atmosphere also behaves like a blackbody, so it emits photons based on its temperature ($P/a = \sigma T^4$). It emits photons equally both upward and downward.
4. Photons emitted by the atmosphere in the upward direction escape to space and carry energy away from the Earth. Photons emitted downward are absorbed by the surface.

This one-layer model is diagramed in Figure 4.5. For conceptual simplicity, the diagram shows the effects of the atmosphere concentrated in a single layer, which is why this model is frequently called a “one-layer” model.

To calculate the surface temperature in this model, we assume that the planet as a whole, as well as the surface and the atmosphere individually, must all be in energy balance (where E_{in} equals E_{out}). First, let us consider the energy balance for the planet as a whole. *Energy in* to the planet is coming entirely from the Sun. *Energy out* to space is coming entirely from the atmosphere (remember: any photons emitted by the surface are absorbed by the atmosphere; they do not escape to space). Using the Earth's values of solar constant and albedo, the *energy in* from the Sun is 238 W/m^2 (Equation 4.2). This means that the atmosphere must be

Figure 4.5 Schematic of energy flow on a planet with a one-layer atmosphere. The atmosphere is represented by a single layer that is transparent to visible photons but absorbs all infrared photons that fall on it. The arrows show global average energy flows with values in W/m^2 , which are based on our Earth's values of solar constant and albedo.



radiating 238 W/m^2 upward to space in order for the planet as a whole to be in energy balance. Because the atmosphere radiates equally upward and downward, the atmosphere is also radiating 238 W/m^2 back toward the Earth's surface.

Now let us consider energy balance for the surface. *Energy in* for the surface is 238 W/m^2 from the Sun and 238 W/m^2 from the atmosphere, for a total of 476 W/m^2 . This means that the surface has to be emitting 476 W/m^2 upward in order to achieve energy balance.

To make sure we did not make a mistake, we can check the energy balance for the atmosphere. *Energy in* comes from the surface, 476 W/m^2 . *Energy out* comes from emission of 238 W/m^2 upward to space and 238 W/m^2 downward to the surface, for a total *energy out* of 476 W/m^2 . Thus, the atmosphere is indeed in energy balance.

So what is the temperature of the surface? If we know that the surface is emitting 476 W/m^2 , we can determine its temperature by using the Stefan–Boltzmann equation from Chapter 3: $E_{\text{out}} = P/a = \sigma T^4$. Solving $\sigma T^4 = 476 \text{ W/m}^2$ for T yields a surface temperature of 303 K (30°C), which is 48°C warmer than that for the planet without an atmosphere.³

This is an incredibly important result: the addition of an atmosphere that is opaque to infrared radiation has significantly warmed the planet's surface. Conceptually, this occurs because the surface of the planet with an atmosphere is heated not just by the Sun but also by the atmosphere. Of course, if you walk outside, you cannot see the atmosphere heating the Earth's surface because the photons the atmosphere emits are not visible, but they still carry energy. When scientists talk about the greenhouse effect, it is this heating of the surface by the atmosphere to which they are referring.

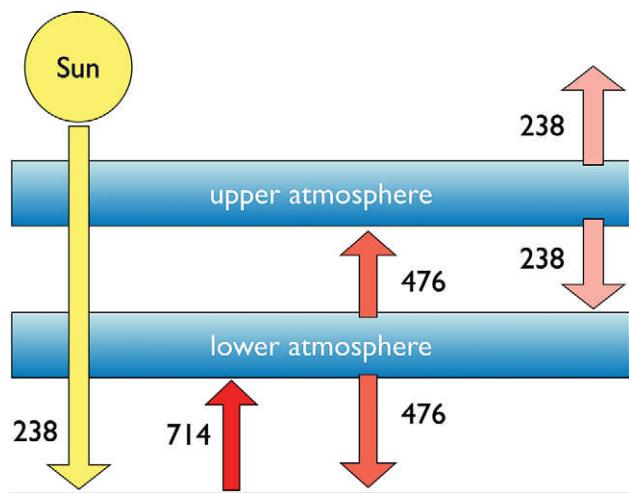
An alternative way to think about the greenhouse effect is that the atmosphere warms the surface by making it harder for the surface to lose energy to space. Without an atmosphere, all of the photons emitted by the surface escape to space; the surface has to emit only 238 W/m^2 for the planet to be in energy balance. With a one-layer atmosphere, though, only half of the photons emitted by the surface end up escaping to space – the other half are returned to the surface. This means that the surface must emit twice as much, 476 W/m^2 , in order for 238 W/m^2 to escape to space. This higher rate of emission requires a warmer surface.

4.3.2 Two-layer Model

Now let us consider a planet with a “two-layer” atmosphere (Figure 4.6). Once again, the atmosphere is transparent to visible radiation but opaque to infrared. That means that photons from the Sun pass through the atmosphere and are absorbed by the surface. Photons emitted by the surface are absorbed in the lower atmosphere. Photons emitted by the lower atmosphere in the upward direction are absorbed by the upper atmosphere; photons emitted in the downward direction are absorbed by the surface. Photons emitted

³ Watch the author go over the one- and two-layer models at www.andrewdessler.com/layermodels

Figure 4.6 Schematic of energy flow on a planet with a two-layer atmosphere, with values in W/m^2 , which are based on our Earth's values of solar constant and albedo.



by the upper atmosphere in the upward direction escape to space; photons emitted in the downward direction are absorbed by the lower atmosphere.

Once again, the key to determining the surface temperature is to enforce energy balance for the planet as a whole, the surface, and both atmospheric layers. The easiest way to do this is to start with planetary energy balance and then work downward from the topmost layer to the surface. Planetary energy balance requires *energy out* for the planet to balance *energy in* from the Sun. Because *energy out* comes entirely from the upper layer, it must be emitting 238 W/m^2 to space in order to balance the 238 W/m^2 that the Sun is providing the planet (again assuming terrestrial values for S and α). That, in turn, means that the upper layer is also emitting 238 W/m^2 downward.

Totaling the emissions in both directions, the upper layer is emitting 476 W/m^2 . Because *energy out* must equal *energy in* for the layer, this layer must be receiving 476 W/m^2 from the lower atmospheric layer. Thus, we know that the lower layer is emitting 476 W/m^2 upward – and therefore downward, too. For the lower layer to achieve energy balance, the lower layer must also be receiving $476 + 476 = 952 \text{ W/m}^2$. We already calculated that 238 W/m^2 are coming from the upper layer, so that means that 714 W/m^2 must be coming from the surface to the lower layer.

We can verify our result by examining the energy balance for the surface. The surface receives 476 W/m^2 from the lower atmosphere and 238 W/m^2 from the Sun, for a total E_{in} of 714 W/m^2 . This corroborates what we calculated must be E_{out} for the surface based on energy balance for the lower atmosphere.

Finally, for the surface to be emitting 714 W/m^2 , its temperature must be 335 K (62°C). This is 32°C warmer than the surface of the planet with a one-layer atmosphere and 80°C warmer than a planet with no atmosphere. Thus, adding a second layer to the atmosphere further increases the planet's surface temperature.

4.3.3 An n -Layer Model

Now let us derive the surface temperature for a planet with n layers (Figure 4.7). For some variety, let us assume that the planet has a solar constant $S = 2,000 \text{ W/m}^2$ and an albedo $\alpha = 0.7$. Thus, *energy in* for this planet is $S(1 - \alpha)/4 = 150 \text{ W/m}^2$. In order to achieve planetary energy balance, upward emission from the topmost layer of the atmosphere (Layer 1) must also be 150 W/m^2 . And because upward and downward emissions must be the same, this layer is also emitting 150 W/m^2 downward, so that total *energy out* for this layer is 300 W/m^2 . This in turn means that *energy in* for Layer 1 must also be 300 W/m^2 .

Energy in for Layer 1 comes entirely from energy emitted by Layer 2. Layer 2 must therefore be emitting 300 W/m^2 upward. This means that it is also emitting 300 W/m^2 downward, for a total *energy out* of 600 W/m^2 . *Energy in* for Layer 2 comes from downward emissions of Layer 1 and upward emissions of Layer 3 and must total 600 W/m^2 in order to balance *energy out*. Downward emissions from Layer 1 are 150 W/m^2 , which means that upward emissions from Layer 3 must be 450 W/m^2 .

Layer 3 must be emitting 450 W/m^2 both upward and downward, for a total *energy out* of 900 W/m^2 . *Energy in* from downward emissions from Layer 2 is 300 W/m^2 , meaning that upward emissions from Layer 4 must be 600 W/m^2 .

By this time, a pattern has emerged, and we can extrapolate to the bottommost layer, layer n . Layer n is emitting $150n$ in both upward and downward directions. This in turn

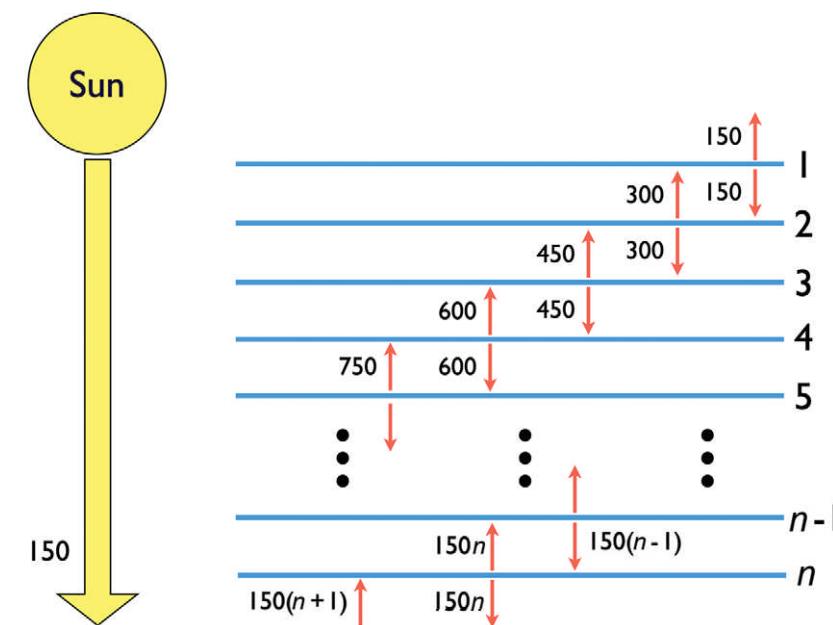


Figure 4.7 Schematic of energy flow on a planet with an n -layer atmosphere; layers are numbered from 1 to n (topmost to bottommost layers), with values in W/m^2 . Fluxes assume a solar constant of $2,000 \text{ W/m}^2$ and an albedo of 0.7.

means that the surface is receiving $150n$ emitted from the bottommost layer and 150 W/m^2 from the Sun. For energy to balance, the surface must be emitting $150(n+1) \text{ W/m}^2$ upward. Setting $150(n+1) = \sigma T^4$, we can solve for the surface temperature T of this planet:

$$T = \sqrt[4]{\frac{150(n+1)}{\sigma}} \quad (4.4)$$

Based on this, we can write the general solution for the surface temperature of an n -layer planet with solar constant S and albedo α :

$$T = \sqrt[4]{\frac{(n+1)S(1-\alpha)}{4\sigma}} \quad (4.5)$$

This is an important and profound equation, and one that is good to memorize. It says that the surface temperature of the planet is basically determined by these three parameters: the number of layers in the atmosphere, the solar constant, and the albedo.

To connect this equation to the real world, I should make clear what the “number of layers” physically represents. As I will discuss in Chapter 5, it is the greenhouse gases in our atmosphere that absorb infrared photons. And the number of layers is equivalent to the amount of greenhouse gas in the atmosphere. Therefore, an increase in the amount of greenhouse gas in the atmosphere corresponds to an increase in the number of layers – and a warming climate.

Before we proceed to testing our theory, it is important to reiterate two important points:

1. We can now answer the question, “Why is the Earth’s temperature what it is?” The temperature of our climate system is set by the requirement that *energy in* and *energy out* balance. So the climate we have is the one that produces energy balance for the Earth.
2. If n , S , or α change, then the temperature will adjust as required to re-establish energy balance. In particular, as you add more greenhouse gases to the planet (i.e., increase n), the temperature of the planet will increase. This very simple physical argument is why scientists are so confident that adding greenhouse gases to the atmosphere will warm our climate.

4.4 Testing Our Theory with Other Planets

It is important to emphasize that the n -layer model discussed in Subsection 4.3.3 makes many simplifying assumptions. For example, we have assumed that all energy transport in our atmosphere is by radiation, but that’s wrong – some energy is transported by atmospheric motions, such as warm air rising in thunderstorms, which carries heat to the upper

Table 4.1 Data on the four inner planets in our Solar System

Planet	Solar constant (W/m ²)	Albedo	Energy in (W/m ²)	Observed surface temperature (K)	Inferred <i>n</i>
Mercury	10,000	0.1	2,250	452	0.052
Venus	2,650	0.7	199	735	82
Earth	1,360	0.3	238	289	0.65
Mars	580	0.15	123	227	0.22

atmosphere (see end-of-chapter problems 20 and 21). Another simplification is that the model assumes infinitely fast horizontal energy transport, allowing us to use a single temperature for the planet. In reality, though, transport of energy is slow enough that large temperature differences can develop between regions (e.g., between the tropics and the polar regions, or between night and day sides of the planet).

This means that you should not expect the model to produce quantitatively accurate surface temperatures. Nonetheless, the model captures the essential physics of our climate system. And, as I will show in this section, the model is successful in explaining the relative surface temperatures of the Earth and its nearby neighbors, Mercury, Venus, and Mars.

Table 4.1 lists the important characteristics of the planets, and it reveals some puzzles. Venus is twice as far from the Sun as Mercury, but it has a surface temperature that is approximately 300 K warmer. This result becomes even more puzzling when we realize that, because of its high albedo, *energy in* for Venus, $S(1 - \alpha)/4 = 199 \text{ W/m}^2$, is less than one-tenth that for Mercury ($2,250 \text{ W/m}^2$). It is even less than the *energy in* for the Earth (238 W/m^2) – yet Venus is 450 K (800°F) hotter than the Earth.

Given the surface temperature, albedo, and solar constant, we can solve Equation 4.5 for *n*, which is the number of layers required to satisfy energy balance (“Inferred *n*” in Table 4.1). The inferred *n* for Mercury is near zero, suggesting it has almost no greenhouse effect. This is correct, because Mercury has essentially no atmosphere. For Mars, inferred *n* = 0.22. This again makes some sense – Mars has a thin atmosphere mostly containing carbon dioxide, so it does have some greenhouse effect. However, the Martian atmosphere has fewer greenhouse gases than the Earth’s atmosphere, so the greenhouse effect on Mars is expected to be weaker than that on Earth. Our calculations confirm that.

Finally, our calculations reveal that Venus, with inferred *n* = 82, has a massive greenhouse effect. This is again correct. The surface pressure on Venus is 90 times that of Earth (1,300 psi, or pounds per square inch, compared with 14.5 psi here on Earth), and the atmosphere is mainly composed of carbon dioxide. The result of this massive,

greenhouse-gas-rich atmosphere is a planet hotter than the inside of your oven on broil – hot enough even to melt lead. The success of Equation 4.5 in successfully explaining the relative climates of the innermost planets of our Solar System should provide us with some confidence that we understand the essential physics of these planets.

4.5 Chapter Summary

- In this chapter, we created a very simple climate model based on the fact that the solar energy received by a planet (E_{in}) must be balanced by the energy that is radiating to space (E_{out}). The temperature of the planet adjusts until this balance is achieved.
- For a planet, $E_{\text{in}} = S(1 - \alpha)/4$. S is the solar constant, which is the intensity of sunlight at the planet's orbit (in units of W/m^2), and α is the planet's albedo, which is the fraction of photons that fall on the planet that are reflected back to space (unitless).
- The *energy out* for a planet is due to blackbody radiation.
- In our simple model of the climate, the atmosphere is entirely transparent to visible radiation from the Sun, but it absorbs all infrared radiation. We further assume that the atmosphere radiates like a blackbody equally in the upward and downward direction. We can then calculate the surface temperature by enforcing energy balance for the surface, the atmosphere, and the planet as a whole.
- We derived a general equation, Equation 4.5, for the surface temperature T of a planet. It is repeated here:

$$T = \sqrt[4]{\frac{(n+1)S(1-\alpha)}{4\sigma}}$$

- This equation says that the surface temperature of the planet is determined by three parameters: the number of layers in the atmosphere (n), which is a proxy for the amount of greenhouse gases in the atmosphere, the solar constant (S), and the albedo (α).
- This simple model also explains the relative temperatures of the Earth's nearest neighbors, namely Mercury, Venus, and Mars.

See www.andrewdessler.com/chapter4 for additional resources for the chapter.

TERMS

Albedo

Greenhouse effect

Solar constant

PROBLEMS

1. What is the surface area of a sphere with radius r ? What is the area of a disk with radius r ? What is the area of a disk with diameter d ?
2. A planet in another solar system has a solar constant $S = 2,000 \text{ W/m}^2$, and the distance between the planet and the star is 100 million kilometers.
 - (a) What is the total power output of the star? (Give your answer in watts.)
 - (b) What is the solar constant of a planet located 75 million kilometers from the same star? (Give your answer in watts per square meter.)
3. Draw a diagram (like Figure 4.5) that shows the energy flows for a planet with a one-layer atmosphere. The solar constant for the planet is $S = 900 \text{ W/m}^2$, and the albedo of the planet is $\alpha = 0.25$. Make sure each arrow is labeled with the energy flow. What is the surface temperature of this planet?
4. Draw a diagram (like Figure 4.6) that shows the energy flows for a planet with a two-layer atmosphere. The solar constant for the planet is $S = 3,000 \text{ W/m}^2$ and the albedo of the planet is $\alpha = 0.1$. Make sure each arrow is labeled with the energy flow. What is the surface temperature of this planet?
5. Two people argue about why Venus is so much warmer than the Earth. The first argues that it is because Venus is closer to the Sun, so it absorbs more solar energy. The second argues that it is because Venus has a thick, greenhouse-gas-rich atmosphere. Which person is right, and why is the other one wrong?
6. Some recently discovered planets in other solar systems are so hot that they glow in the visible; they are literally “red hot” (e.g., do a Google search for “HD 149026b”).
 - (a) How many atmospheric layers would the Earth need before it glowed in the visible? (Assume $S = 1,360 \text{ W/m}^2$ and $\alpha = 0.3$.) To answer this, you must first estimate what temperature the Earth has to be to begin glowing.
 - (b) Alternatively, what would the solar constant have to increase to for a one-layer planet with an albedo $\alpha = 0.3$?
 - (c) How far would the Earth have to be from the Sun in order to have this solar constant?
7. Assume a planet with a one-layer atmosphere has a solar constant $S = 2,000 \text{ W/m}^2$ and an albedo $\alpha = 0.4$.
 - (a) What is the planet’s surface temperature? Make the standard assumption that the atmosphere is transparent to visible photons but opaque to infrared photons.
 - (b) During a war on this planet, a large number of nuclear weapons are exploded, which kicks enormous amounts of dust and smoke into the atmosphere. The

net result is that the atmosphere now absorbs visible radiation – so solar energy is now absorbed in the atmosphere. It also still absorbs infrared radiation. Draw a diagram like Figure 4.5 to show the fluxes for this new situation, and calculate the planet’s surface temperature. The solar constant and albedo remain unchanged.

(c) Explain in words why the temperature changes the way it does after the nuclear war. Is describing this as “nuclear winter” appropriate?

8. Assume a planet with a one-layer atmosphere and values of solar constant $S = 1,000 \text{ W/m}^2$ and albedo $\alpha = 0.25$. Let us assume there is some dust in the atmosphere, so that 50 percent of the Sun’s energy is absorbed by the atmosphere and 50 percent by the surface. Draw a diagram like Figure 4.5 to show the fluxes, and calculate the planet’s surface temperature.

9. Derive an expression for the fraction of energy received by the surface that comes from the atmosphere (this is the amount of energy that comes from the atmosphere divided by the sum of energy from the Sun and energy from the atmosphere). Using values in Table 4.1, calculate the fraction for Mercury, Earth, and Venus. Make the standard assumption that the atmosphere is transparent to visible photons but opaque to infrared photons.

10. On Mercury, which has no atmosphere, the difference in temperature between daytime and nighttime temperatures can be 700 K. On the Earth, the difference between daytime and nighttime temperatures can be 30 K. On Venus, there is basically no difference between daytime and nighttime temperatures. Why is this? Hint: consider how much of the surface energy budget comes from the atmosphere versus the Sun. If you get stuck, working Question 9 might help you answer this question.

11. As we will discover in Chapter 11, one way to solve global warming is to increase the reflectivity of the planet (I will explain how in Chapter 11). To reduce the Earth’s temperature by 1 K, how much would we have to change the albedo? (Assume a one-layer planet with an initial albedo of 0.3 and solar constant of $1,360 \text{ W/m}^2$.)

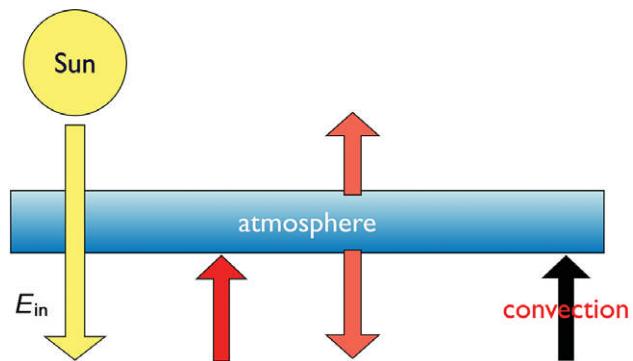
12. Given fixed n and α , how does the temperature of a planet vary with r , the distance between the planet and the star? Hint: Work out how S varies with r , and plug that into Equation 4.5.

13. A planet has a solar constant $S = 2,000 \text{ W/m}^2$, an albedo $\alpha = 0.7$, and a radius $r = 3,000 \text{ km}$. What would happen to the temperature if the planet’s radius doubles?

14. One argument you hear against mainstream climate science is that adding greenhouse gases to the atmosphere is like painting a window. Eventually, the window is opaque, so that adding another coat of paint does nothing. Is this a good analogy? Is there a point where adding greenhouse gases to the atmosphere does not lead to increases in the planet’s temperature?

15. Imagine that the Sun's radius doubles (but the Sun maintains the same surface temperature). What happens to the Earth's solar constant and surface temperature? You can assume that the Earth's original surface temperature is 288 K.
16. Does the variation of solar energy with surface orientation (Figure 4.3) explain the variation in local temperature through the day? The warmest temperatures during the day are usually found from 3 PM to 5 PM; what might explain that?
17. If you were on a spacecraft and you pointed an infrared thermometer at a one-layer planet, what temperature would it read? What if the planet had two layers? Or n -layers? Assume S and α are the same as for the Earth. Remember that an infrared thermometer measures the radiation coming from an object and yields the temperature the object must be in order to be emitting that radiation.
18. Newly formed stars are often obscured by the dense dust clouds from which they form. To see how these appear to observers on the Earth, imagine that 50 stars, each identical to our Sun, form in a spherical cloud of dust with a radius of 100 billion kilometers. Much like the atmosphere, the dust absorbs all of the light given off by the stars and radiates an equal amount of energy to the rest of the Universe. What temperature does the cloud appear to be from outside the cloud? What wavelength telescope would you need to see the dust cloud?
19. (a) How much land (in km^2) would you need to cover with solar panels in order to generate all of our power from solar energy (assume human power consumption is 15 TW). If one takes into account the day-night cycle and occasional cloudiness, solar panels receive (on average) about 200 W/m^2 of sunlight. And this is further reduced because these panels convert sunlight into electricity with an efficiency of about 20 percent.
(b) What fraction of the Earth would you need to cover with solar panels? Does this seem possible?
20. The simple model we developed in this chapter assumes all energy transport in our atmosphere is by radiation. In the real atmosphere, however, other transport pathways exist. One neglected pathway is convection, such as thunderstorms, which carry energy from the surface to the atmosphere. For this problem, assume that a planet with a one-layer atmosphere has an *energy in* of 300 W/m^2 .
 - (a) If we assume the only energy transport is by radiation (Figure 4.5), what is the surface temperature of the planet?
 - (b) Let's assume that convection occurs on this planet (Figure 4.8) and it carries 80 W/m^2 from the surface to the atmosphere. How does this change the other fluxes (relative to a planet with no convection)?
 - (c) What is the surface temperature of the planet with convection? In one sentence, what is the impact of convection on the surface temperature?

Figure 4.8 Schematic of energy flow on a planet with a one-layer atmosphere that includes convection. The arrow marked “convection” represents dynamic processes that transport energy from the surface to the atmospheric layer.



21. A more advanced convection problem: In reality, moist convection ties the atmospheric temperature to the surface temperature. If we assume that the temperature of the atmosphere is always 30 K cooler than the surface temperature, what is the value of the fluxes in Figure 4.8? What is the surface temperature of this planet? Assume for this problem that E_{in} is 350 W/m².

5

The Carbon Cycle

In the simple model of the climate presented in Chapter 4, the temperature of a planet is set by the number of atmospheric layers (n), the albedo, and the solar constant. I said there that the number of layers is determined by the abundance of greenhouse gases in the atmosphere, but I was intentionally vague about what a greenhouse gas is, or which components of our atmosphere are greenhouse gases. In this chapter, I address these questions and discuss in detail the key greenhouse gas for the problem of modern climate change, carbon dioxide.

Carbon dioxide, or CO_2 , is the primary greenhouse gas emitted by human activities, and policies to control modern climate change frequently focus on reducing our emissions of this gas. But constructing rational climate change policies requires more than just knowing how much of it humans are dumping into the atmosphere. It also requires an understanding of the *carbon cycle* – how carbon moves between the atmosphere, ocean, land biosphere, and rocks on the Earth. This will help us understand what happens to carbon dioxide after it is emitted into the atmosphere, which in turn will help us understand the future trajectory of our climate as well as our ability to head off dangerous climate change.

5.1 Greenhouse Gases and Our Atmosphere's Composition

As we learned in Chapter 4, the greenhouse effect occurs because our atmosphere is mostly transparent to visible photons but absorbs infrared photons. It turns out that only a few of the components of our atmosphere actually absorb infrared photons, and it is these *greenhouse gases* that are responsible for the Earth's greenhouse effect. In this section, I describe the composition of our atmosphere, with a particular focus on greenhouse gases.

Approximately 78 percent¹ of the dry atmosphere (this excludes water vapor) is made up of diatomic nitrogen or N_2 , which is two nitrogen atoms bound together. About 21 percent is diatomic oxygen or O_2 , which is two oxygen atoms bound together; this is the part of the atmosphere that we need to breathe to survive. Argon atoms make up approximately 1 percent of our atmosphere. None of these three constituents, which together make up more than 99 percent of the dry atmosphere, absorbs infrared photons, so they are not greenhouse gases; therefore, they do not warm the surface of the planet.

The next biggest component of the atmosphere is water vapor or H_2O , a constituent whose abundance varies widely from place to place. In the warm tropics, water vapor can

¹ Throughout this section, the percentages given are of volume, not mass. For the chemists reading this, this is the same as mole fraction.

make up as much as 4 percent of the atmosphere. In cold polar regions, in contrast, water vapor may be only 0.2 percent. Its abundance decreases rapidly with altitude, and in the stratosphere it typically makes up 0.0005 percent of the atmosphere.

Water vapor is the most abundant and important greenhouse gas in our atmosphere, and much of the warmth we enjoy on the Earth is due to the heating from water vapor. Its main source is evaporation from the oceans, and it is primarily removed from the atmosphere when water falls out of the atmosphere as rain or snow. Because the amount of water vapor in the atmosphere is regulated by evaporation and condensation, it is essentially set by the Earth's temperature – if the Earth warms, the amount of water vapor in the atmosphere increases. If the Earth cools, the opposite happens and the amount of water vapor in the atmosphere decreases. Emissions of water vapor from human activities contribute essentially nothing to its atmospheric abundance. In Chapter 6, we will see that water vapor acts as a feedback to amplify warming from the addition of greenhouse gases like carbon dioxide to the atmosphere.

Taken together, diatomic nitrogen and oxygen, water vapor, and argon make up more than 99.95 percent of the atmosphere. You might expect the remaining 0.05 percent to have no important role because it seems like such a small amount, but you would be wrong. This last smidgen of atmosphere is crucial to life on the planet.

The largest part of this remaining 0.05 percent is carbon dioxide or CO₂, which makes up 0.041 percent of the atmosphere. Carbon dioxide absorbs infrared photons and is the second most important greenhouse gas, behind water vapor – *but it is the most important greenhouse gas that humans directly influence* and therefore is the primary cause of modern climate change.

Because 0.041 percent is an awkwardly small number, scientists typically express the concentration of these trace gases in a more convenient unit: *parts per million*. A concentration expressed in parts per million indicates how many molecules out of every million are the gas in question.² Parts per million can be usefully contrasted with percent, which comes from the marriage of the words *per cent*, literally meaning “out of 100.” Thus, air is approximately 78 percent diatomic nitrogen, which means that 78 out of every 100 molecules of air are molecules of nitrogen.

In this case, the carbon dioxide abundance when I am writing this in 2020 is 0.0412 percent, corresponding to 412 parts per million or ppm. Put another way, there were 412 molecules of carbon dioxide in every million molecules of air. This number is rising around 2 ppm per year, so by the time you read this, it will certainly be higher.

The next most important greenhouse gas in our atmosphere is methane or CH₄. In 2020, it had an atmospheric abundance of 1.87 ppm. Despite its small abundance, methane is also a key player in our climate, as we will discuss later. Another important greenhouse gas in our atmosphere is nitrous oxide or N₂O, which is present in today's atmosphere at concentrations of about 0.32 ppm. This molecule is also known as

² Parts per million can be by volume (number of molecules out of every million) or by mass (grams of constituent out of every million grams of air). Following the previous discussion, all mixing ratios in this book will be by volume.

“laughing gas,” which your dentist might give you before she works on your teeth. It is emitted into the atmosphere from nitrogen-based fertilizer and industrial processes as well as having several natural sources.

Ozone is another important greenhouse gas in our atmosphere. Its chemical formula is O_3 , so it is a molecule made up of three oxygen atoms. The abundance of ozone varies widely across the atmosphere – in unpolluted air near the surface, its abundance is about 10–40 parts per billion,³ whereas its abundance can reach 10 ppm in the stratosphere. Ozone is absolutely essential for life on our planet because it absorbs high-energy ultraviolet photons emitted by the Sun before they reach the Earth’s surface. These photons carry enough energy that they can seriously damage living tissue – leading to diseases such as skin cancer in humans. But ozone is also one of the primary components of photochemical smog, and breathing it can lead to health problems in humans and animals; ground-level ozone can also damage plants. Thus, you want ozone between yourself and the Sun, but you do not want to breathe it. Because of this, ozone high up in the stratosphere is considered “good” ozone, whereas ozone near the ground is “bad” ozone.

A final group of greenhouse gases are the halocarbons, including chlorofluorocarbons and hydrochlorofluorocarbons, which are synthetic industrial chemicals used as refrigerants (e.g., in air-conditioners and refrigerators) and in various industrial applications, as well as natural molecules such as methyl chloride. Together, they are present in today’s atmosphere at a concentration of a few parts per billion. One might be tempted to think that a gas that has an abundance of a few parts per billion cannot be important in our climate. As we’ll cover in Section 5.8, despite their low concentration these gases have a powerful impact on our climate. Halocarbons also include the chemicals that are the main culprits behind ozone depletion.

As we will discuss further in the next chapter, carbon dioxide is the most important greenhouse gas for the problem of modern climate change. Because of that, we focus here mainly on that gas and the processes that regulate its atmospheric abundance, which are collectively known as the *carbon cycle*.

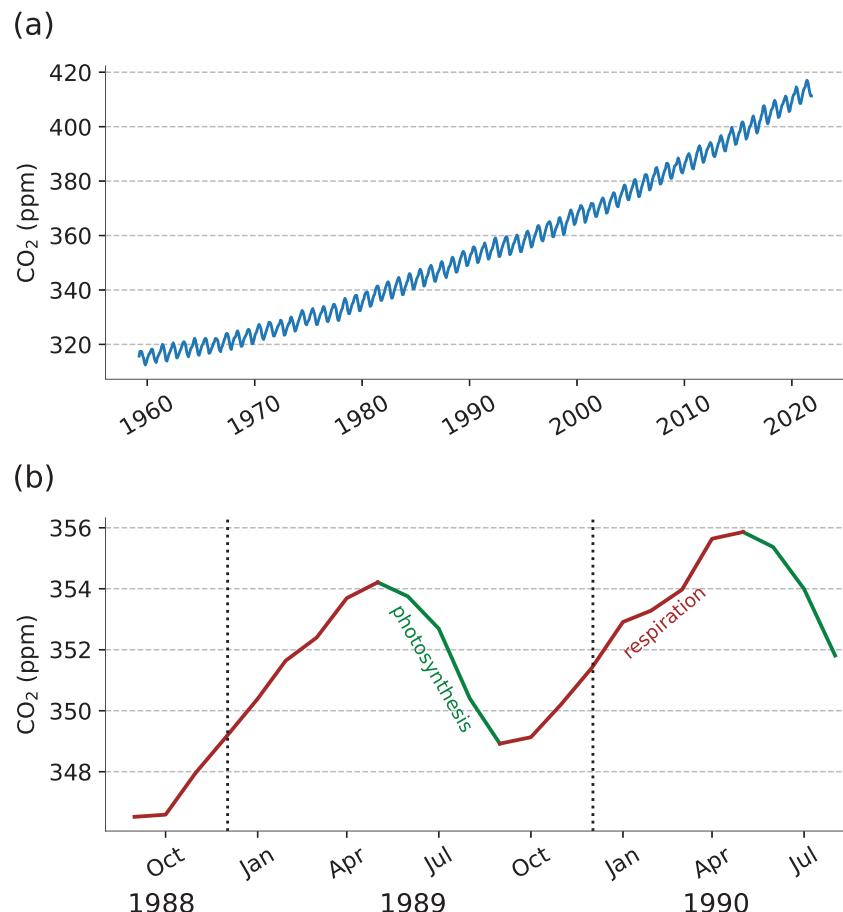
5.2 Atmosphere–Land Biosphere–Ocean Carbon Exchange

5.2.1 Atmosphere–Land Biosphere Exchange

We have been directly monitoring the abundance of carbon dioxide in the atmosphere since the middle of the twentieth century. The measurements are plotted in Figure 5.1a, which is often referred to as the *Keeling curve* after Charles D. Keeling, the scientist who initiated the measurements in 1957. The measurements clearly see a long-term upward trend. That means that the number of layers, n , of the Earth is increasing. Based on what you learned in

³ This means that, of every billion molecules of air, 10–40 are ozone.

Figure 5.1 (a) The record of atmospheric carbon dioxide since the middle of the twentieth century. (b) Close-up of two years: fall 1988 through fall 1990. Periods dominated by photosynthesis are green and periods dominated by respiration are brown. Data measured at Mauna Loa, Hawaii by Dr. Pieter Tans, NOAA/GML and Dr. Ralph Keeling, Scripps Institution of Oceanography. Data downloaded from the NOAA Earth System Research Laboratory/ Global Monitoring Division (www.esrl.noaa.gov/gmd/ccgg/trends/data.html, retrieved November 29, 2020).



Chapter 4, you should be comfortable predicting that the climate should be warming – and, as we saw in Chapter 2, it is.

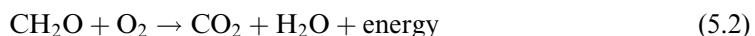
We will return to the upward trend later in the chapter. In this subsection, however, we’re going to focus on the “sawtooth” annual cycle. Figure 5.1b plots a close-up of 2 years (24 months) of measurements, showing that the amount of carbon dioxide in the atmosphere varies, with a maximum in May, when carbon dioxide is about 6 ppm higher than the minimum in September. This annual cycle in carbon dioxide reflects the annual cycle of plant growth and decay. Plants absorb carbon dioxide from the atmosphere and use it to produce more plant material in a process known as *photosynthesis*:



In this reaction, carbon dioxide, water, and sunlight combine to produce CH₂O and O₂. Because CH₂O is a combination of carbon and water, molecules made up of this unit are

generally referred to as carbohydrates – in this context, you can think of CH_2O as the chemical formula for a plant. Diatomic oxygen produced in this reaction is released into the atmosphere. This is the main source for the oxygen in our atmosphere, which you are breathing right now.

At the same time, humans, animals, and bacteria consume plant material in order to produce energy through a reaction known as *respiration*:



The products of respiration are carbon dioxide, which is released back into the atmosphere, water vapor, and energy, which is used to power the organism. It should be noted that Equations 5.1 and 5.2 are simplified reactions that stand in for a large number of complex biochemical reactions that occur within the cells of organisms.

Equation 5.2 is the reverse of Equation 5.1: the carbon dioxide consumed in the production of the plant material in Equation 5.1 is released back into the atmosphere when the plant is consumed in Equation 5.2. Similarly, the oxygen molecule produced in Equation 5.1 is consumed in Equation 5.2. The production of a carbohydrate through photosynthesis followed by its consumption during respiration therefore produces no net change in either carbon dioxide or oxygen. Instead, the net effect is the conversion of sunlight into energy to power living creatures.

The atmosphere contains approximately 864 gigatonnes of carbon (GtC) (all reservoir values in this section are values averaged over 2008–2017). A gigatonne is 1 billion metric tonnes, where 1 metric tonne is 1,000 kg or 2,200 lb. Note that this is just the mass of the carbon atoms in the atmosphere – although the carbon dioxide molecule also contains two oxygen atoms, their mass is not included.

The land biosphere contains 2,150 GtC, about 2.5 times more than found in the atmosphere. This carbon is stored in living plants and animals and in organic carbon in soils (e.g., decaying leaves). During a given year, photosynthesis removes approximately 110 GtC from the atmosphere. Respiration roughly balances this, transferring about the same amount back to the atmosphere. Thus, over a year, there are only small changes in carbon dioxide in the atmosphere or land biosphere as a result of photosynthesis or respiration.

The fact that photosynthesis and respiration are balanced over the year does not mean that they are in balance at every point in time. Most of the Earth's land area – and, therefore, most of the Earth's plants – are found in the northern hemisphere. During the northern hemisphere's spring and summer (May–September), when plants are growing and trees are leafing, global photosynthesis exceeds respiration and there is a net drawdown of carbon dioxide out of the atmosphere and into the land biosphere; we can see this in Figure 5.1b.

During the northern hemisphere's fall and winter (October–April), plant material that was produced during the spring and summer decays, releasing carbon dioxide back into the atmosphere. During this period, global respiration exceeds photosynthesis, and there

is a net transfer of carbon from the biosphere into the atmosphere, which we can also see in Figure 5.1b. This annual cycle in plant growth is the origin of the “sawtooth” annual cycle.

There is also a large amount of carbon stored in permafrost (1,400 GtC), which is ground that is frozen year-round. Much like that frozen dinner that has been in your freezer since Barack Obama was President, dead organic plant matter frozen into the permafrost does not decay; it is kept intact as long as the ground remains frozen. If permafrost thaws, however, the organic matter stored there will begin to decay, releasing carbon into the atmosphere.

Aside 5.1: Where does the oxygen in our atmosphere come from?

As I mentioned earlier, photosynthesis followed by respiration is not a net producer or consumer of carbon dioxide or oxygen. Where, then, does the large amount of diatomic oxygen in our atmosphere come from? It turns out that it is the result of photosynthesis that is not balanced by respiration. That occurs when a plant grows through photosynthesis, but the plant material is buried before it can be consumed via respiration. When that happens, the oxygen produced during photosynthesis is not consumed. Over the billions of years that life has existed on the planet, this process has built up and now maintains the atmospheric oxygen levels we enjoy today.

5.2.2 Atmosphere–Ocean Carbon Exchange

One of carbon dioxide’s most important properties is that it readily dissolves in water. Once it has dissolved in water, carbon dioxide is then converted to *carbonic acid* (H_2CO_3) by means of this reaction:



The carbonic acid formed in Equation 5.3 can react further with water to convert into other forms of carbon. Because of the conversion of carbon dioxide to many other forms of carbon, the ocean can absorb huge amounts of carbon dioxide. Carbon is returned to the atmosphere in a reaction that is the reverse of Equation 5.3, in which carbonic acid converts back to carbon dioxide and water:



This is followed by the escape of carbon dioxide back into the atmosphere. Processes embodied by Equations 5.3 and 5.4 transfer about 60 GtC per year between the atmosphere and ocean.

Thus, carbon cycles easily between the atmosphere and ocean. To fully understand this exchange, however, it is best to think of the ocean as being split into two parts. The first part is the top 100 m or so of the ocean, which exchanges carbon rapidly with the atmosphere. This part of the ocean makes up only a few percent of the mass of the ocean and is often referred to as the *mixed layer* because it is well mixed by winds and other weather events; it contains 900 GtC.

Below this lies the other 97 percent of the ocean, known as the *deep ocean*. The deep ocean also contains most of the ocean's carbon, 37,100 GtC, or 43 times more carbon than is in the atmosphere. The mixed layer exchanges carbon with the deep ocean at a rate of about 100 GtC per year. This occurs as ocean currents mix high-carbon water from the mixed layer with low-carbon water from the deep ocean. It also occurs when sinking organic matter, such as dead organisms or fecal material, falls from the mixed layer into the deep ocean – a process known as the biological carbon pump.

5.2.3 The Combined Atmosphere–Land Biosphere–Ocean System

Figure 5.2 shows a schematic of the combined atmosphere–land biosphere–ocean system. Approximately 110 GtC per year are continuously cycling between the atmosphere and land biosphere as plants absorb carbon dioxide as they grow and then release carbon dioxide when they die. About 60 GtC per year of carbon cycles between the atmosphere and the ocean's mixed layer. At the same time, the mixed layer and deep ocean are exchanging 100 GtC per year.

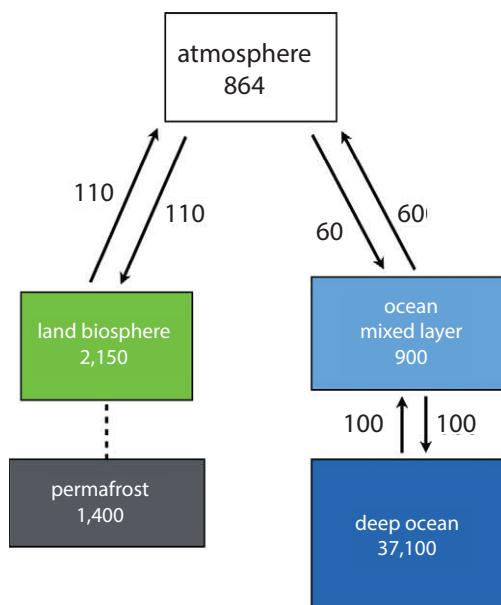


Figure 5.2 A schematic of exchange between the atmosphere, land biosphere, and ocean. Numbers in the boxes represent the amount of carbon stored in each reservoir, in GtC. Arrows represent fluxes, with values in GtC per year.

To get an idea of what these numbers actually mean, it is useful to calculate how fast carbon is flowing through these reservoirs.

To do this, we calculate *turnover times*. To understand this concept, let's go back to the bank account analogy we used to explain energy balance in Chapter 3. If you have \$1,000 in your account and you spend \$100 per month, while also depositing \$100 per month, then your bank balance is not changing from month to month. However, there is money *flowing through your account*, and we can estimate a turnover time for your account as the balance divided by the rate. In this case, it would be \$1,000 divided by \$100 per month, or a turnover time of 10 months. Put a different way, this means that enough exchange will take place to replace all of the dollars in your account every 10 months.

We can apply this concept to carbon cycling between the atmosphere, land and ocean reservoirs. The turnover time for the atmosphere can be roughly estimated as the size of the reservoir, 864 GtC, divided by the total flux out of the reservoir, 170 GtC per year (110 GtC per year goes into the land biosphere and 60 GtC per year goes into the ocean mixed layer). This yields an atmospheric turnover time of about 5 years. This means that a carbon atom stays in the atmosphere for about 5 years or so before it is transferred into the land biosphere or ocean. Remember that this is an average value – individual molecules of carbon dioxide may remain in the atmosphere for a shorter or longer time.

The turnover time of carbon in the land biosphere is 2,150 GtC divided by 110 GtC per year = 20 years. This means that a carbon atom in the land biosphere will stay there, on average, for 20 years before being transferred into the atmosphere. Thus, it takes a few decades for a carbon atom to make a round trip from the land biosphere into the atmosphere and back into the land biosphere.

We can also calculate the turnover times for the ocean reservoirs. The total flux out of the mixed layer is 160 GtC per year (60 GtC per year is exchanged with the atmosphere and 100 GtC per year is exchanged with the deep ocean), so the turnover time for the mixed layer is $900 \text{ GtC} \div (160 \text{ GtC per year}) = 6 \text{ years}$. The turnover time for the deep ocean is several centuries: $37,100 \text{ GtC} \div (100 \text{ GtC per year}) = 371 \text{ years}$. Thus, it takes a few centuries for a carbon atom to make a round trip from the atmosphere through the mixed layer, the deep ocean, and back.

Another way to think about this is that the atmosphere exchanges carbon rapidly (time scale of years to decades) with the land biosphere and mixed layer, and much more slowly (time scale of centuries) with the deep ocean. Later in the chapter, I will explain why these time constants are so important for the climate change problem.

5.3 Atmosphere–Rock Exchange

Most of the carbon in the world – many millions of gigatonnes of carbon – is stored in rocks, such as limestone (CaCO_3), and this carbon slowly exchanges with the atmosphere–land biosphere–ocean system (Figure 5.3). Carbon dioxide is transferred from rocks directly into

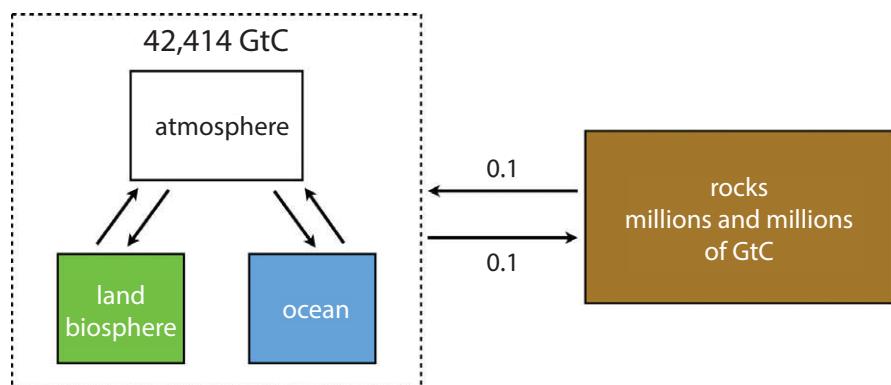


Figure 5.3 A schematic of exchange between the combined atmosphere–land biosphere–ocean reservoir and the rock reservoir. Arrows represent fluxes, with values in GtC per year.

the atmosphere by volcanic eruptions. This process releases an average of 0.1 GtC per year. Although this flux is small compared with other fluxes, over millions of years it can move huge amounts of carbon into the atmosphere–land biosphere–ocean system.

These natural emissions of carbon dioxide from the rock reservoir are roughly balanced by a process known as *chemical weathering*, which removes about an equal amount of carbon from the atmosphere and transfers it back into rocks. Chemical weathering starts when carbon dioxide in the atmosphere dissolves into raindrops falling toward the surface (remember that carbon dioxide dissolves readily in water). Carbonic acid (H_2CO_3) is produced in the raindrop via Equation 5.3, which makes the rain slightly acidic ($\text{pH} = 5.6$).

When this acidic rain falls on rocks, both the physical impact of the rain and chemical reactions break the rock down. A schematic chemical reaction is:

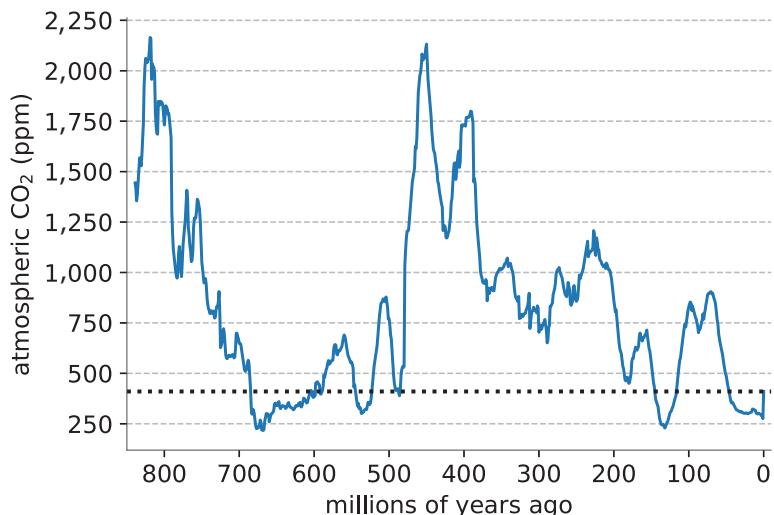


Note that this equation is a general description of the process of weathering, not the exact chemical reaction. Nonetheless, the essential message of Equation 5.5 is correct: The carbon dioxide molecule consumed in this reaction comes from the atmosphere, via rainwater, and it is transferred into a molecule of calcium carbonate (CaCO_3), which is chalk or limestone, and subsequently runs off with the rainwater, eventually reaching the ocean. The reaction also forms silicon dioxide (SiO_2), the primary component of sand, quartz, and glass.

Once in the ocean, the molecules of calcium carbonate are deposited through various mechanisms on the sea floor. Over many millions of years, plate tectonics carries this calcium carbonate deep within the Earth, where high temperatures and pressures turn the rock into magma. Eventually, this carbon is transferred back to the surface by volcanism, thereby releasing the carbon dioxide back to the atmosphere and completing the cycle.

Chemical weathering moves about 0.1 GtC per year from the atmosphere into the rock reservoir, about balancing the volcanic transfer in the other direction.

Figure 5.4 Atmospheric carbon dioxide over the past 850 million years, in ppm. The dotted line is the atmospheric abundance in 2020, 410 ppm. Based on Figure 1 of Foster et al. (2017).



A carbon atom will remain in the atmosphere–land biosphere–ocean system for approximately $42,000 \text{ GtC} \div (0.1 \text{ GtC per year}) = 420,000$ years before it is transferred into the rock reservoir.

Figure 5.4 shows an estimate of atmospheric carbon dioxide over the past 850 million years. The abundance in 2020, 410 ppm, is relatively low when compared to the billion-year geologic record (although today's value is higher than it has been for several million years). During previous periods, atmospheric carbon dioxide reached more than five times higher than today's atmospheric amount.

On the geologic time scales of Figure 5.4, the variations in carbon dioxide are largely due to changes in the rate of cycling between the atmosphere and rock reservoirs. This includes variations in the rate at which carbon dioxide is emitted from volcanoes – during periods of extreme volcanism, for example, atmospheric carbon dioxide will increase — or variations in the rate of chemical weathering.

Variations in the rate of chemical weathering can be caused by the movement of the continents. For example, approximately 40 million years ago, the Indian subcontinent collided with the Asian continent, forming the Himalayas and the adjacent Tibetan Plateau. Changing wind patterns brought heavy rainfall onto the expanse of newly exposed rock. This increase in rainfall sped up the rate of chemical weathering, and the result was a long-term decline in the amount of carbon dioxide in our atmosphere.

5.4 How Are Humans Perturbing the Carbon Cycle?

As Figure 5.4 shows, carbon dioxide varies without any human activities. But, as we show in this section, humans can also affect the carbon cycle. Figure 5.5 shows the perturbed carbon cycle, with the flows of carbon caused by human activities indicated as the red lines.

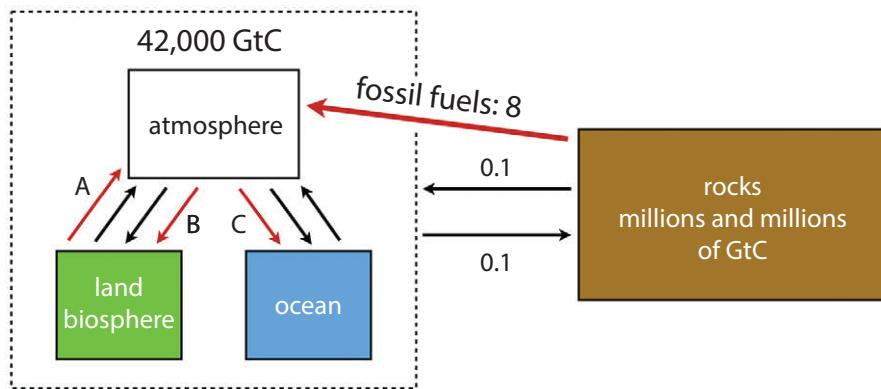


Figure 5.5 Diagram of the carbon cycle as perturbed by humans. Red arrows show net flows of carbon caused by human activities. Red arrows A, B, and C represent deforestation, enhanced absorption of carbon by the land biosphere, and enhanced absorption of carbon by the ocean, respectively.

The main perturbation comes from the combustion of *fossil fuels* for energy. Fossil fuels were formed when plants that grew hundreds of millions of years ago were buried before the carbon in them could be released back into the atmosphere by respiration (this is the same process that leads to a net production of oxygen, discussed earlier). Under high pressure and heat, applied over millions of years, the carbon in the plants was converted into the substances we know today as oil, coal, and natural gas.

When fossil fuels are burned, the net reaction is similar to the respiration reaction (Equation 5.2):



Fossil fuels are represented in Equation 5.6 by CH_x because they are primarily carbon, with varying amounts of hydrogen (which is why they're often referred to as hydrocarbons). During combustion, the fossil fuel combines with oxygen to produce energy, carbon dioxide, and an amount of water vapor that depends on how much hydrogen was in the fuel. The resulting energy is used to power our world, and the carbon dioxide is vented directly into the atmosphere. Fossil fuels can also contain other trace species, such as sulfur. When burned, these trace species can also be released into the environment and lead to environmental problems of their own, such as acid rain. Note that Equation 5.6 is a schematic reaction, not an actual chemical reaction, so do not be concerned that it does not balance.

Before humans discovered them, fossil fuels were safely sequestered in the rock reservoir. The natural carbon cycle would have slowly released this carbon back to the atmosphere through geologic processes over many millions of years. Humans, however, are extracting and combusting fossil fuels at a breath-taking pace – fast enough that we will extract and burn most of the world's easily accessible fossil fuels in a few hundred years. The result is the creation of an additional pathway for carbon from rocks to the atmosphere (the line marked

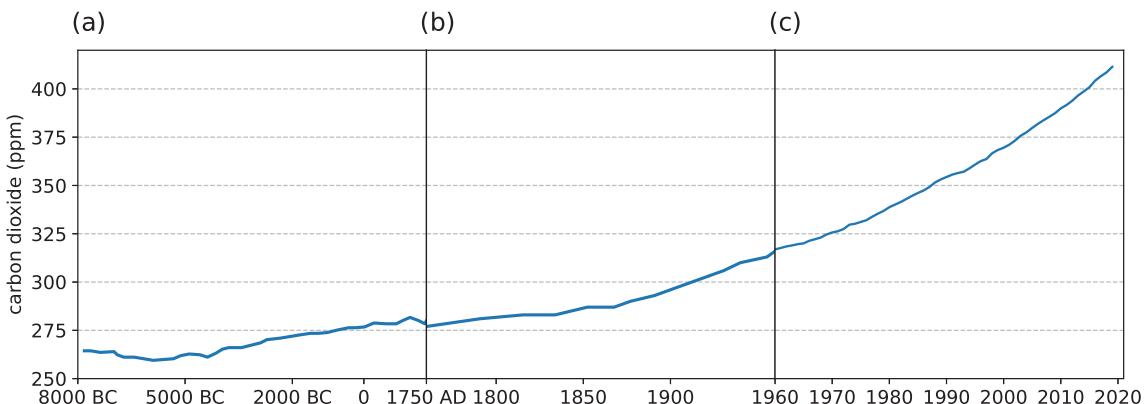


Figure 5.6 Abundance of annual-average carbon dioxide in our atmosphere (a) from 8000 BC to 1750 AD, (b) 1750–1960 AD, and (c) 1960–2020. Panels a and b are adapted from Figure SPM.1 of IPCC, 2007; data in panel c were measured at Mauna Loa, Hawaii by Dr. Pieter Tans, NOAA/GML and Dr. Ralph Keeling, Scripps Institution of Oceanography. Data downloaded from the NOAA Earth System Research Laboratory/Global Monitoring Division (www.esrl.noaa.gov/gmd/ccgg/trends/data.html, retrieved November 29, 2020).

“fossil fuels” in Figure 5.5). And this pathway is huge: over the period 2008–2017, the combustion of fossil fuels led to average emissions of approximately 9.5 GtC per year to the atmosphere.⁴ This is nearly 100 times the natural flow rate of carbon from the rock reservoir to the atmosphere via volcanoes.

Humans have also been chopping down large tracts of forest – a process known as *deforestation* – in order to use the land for other activities, such as agriculture or grazing livestock. Frequently, the forest is removed by burning it, which releases the carbon stored in trees and other plants to the atmosphere. Even just bulldozing the forest releases the carbon to the atmosphere, albeit more slowly. In addition, the soil often contains large amounts of carbon stored in the form of dead organic plant material. When the forest is removed, this plant material can decompose following Equation 5.2, releasing the carbon back into the atmosphere.

Deforestation is just one of many ways that man’s impact on the land can influence atmospheric carbon dioxide. Emissions associated with these changes are known collectively as *land-use changes*. Land-use changes are an important source of carbon dioxide for the atmosphere, and estimates are that it contributed approximately 1.5 GtC per year to the atmosphere from 2008 to 2017 – about one-sixth of the emissions from fossil fuel combustion. This flux is shown in Figure 5.5 as Arrow A.

Figure 5.6a shows that the abundance of carbon dioxide in our atmosphere has remained in a narrow range, 260–280 ppm, from 8000 BC until about 1800 AD. Beginning around that time, however, carbon dioxide began rising (Figure 5.6b). This coincides with the industrial revolution, when widespread burning of fossil fuels began.

⁴ Cement production is lumped into this number; it makes up a few percent of this total.

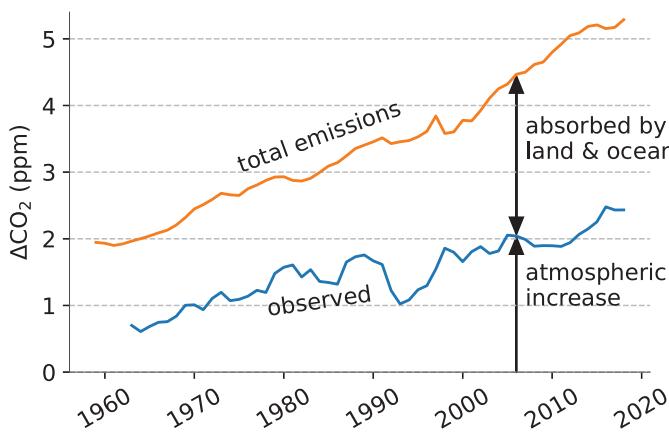


Figure 5.7 The amount of carbon dioxide released into the atmosphere by human activities (orange line) and the observed annual increase in atmospheric carbon dioxide (blue line). Emissions data are described by Friedlingstein et al. (2019) and were downloaded from www.icos-cp.eu/global-carbon-budget-2019, retrieved June 9, 2020. Observations of atmospheric carbon dioxide were obtained from the NOAA Earth System Research Laboratory/Global Monitoring Division and were downloaded from www.esrl.noaa.gov/gmd/ccgg/trends/data.html, retrieved October 11, 2020.

Figure 5.6c shows annual averages of the abundance of carbon dioxide in our atmosphere beginning in 1960. It clearly shows a long-term increase in carbon dioxide also seen in Figure 5.1a, from 315 ppm in 1960 to 410 ppm in 2020, caused by fossil fuel combustion and land-use changes.

We now want to understand the historical view in Figure 5.6 in terms of the carbon cycle. The blue line in Figure 5.7 shows the observed year-to-year increase in atmospheric carbon dioxide. In the late 1950s, the carbon dioxide was increasing at less than 1 ppm per year. By the late 2010s, atmospheric carbon dioxide was increasing by 2.5 ppm per year.

Now we can try to “balance the books,” as an accountant might say. We have good records of exactly how much fossil fuel is extracted and burned each year, so we can know how much atmospheric carbon was added to the atmosphere; this is plotted as the orange line in Figure 5.7. As the plot shows, the increase in atmospheric carbon dioxide was on average only 44 percent of what we were emitting.

This is a puzzle – it’s as if you deposited \$10 in your bank account, but the balance only went up by \$4.40. Where did the rest of our carbon dioxide emissions go? It turns out that the increase in atmospheric carbon dioxide is less than expected because the carbon cycle is continuously pulling carbon out of the atmosphere. About half of this “missing carbon” is dissolving into the ocean, indicated by Arrow C in Figure 5.5. The other half is going into the land biosphere (Arrow B).

The absorption of carbon dioxide by the atmosphere and ocean is doing us a tremendous favor. If those reservoirs were not absorbing some of the carbon we emit every year, the amount of carbon dioxide in the atmosphere today would be much higher and the climate would consequently be a lot warmer. However, this comes with a cost. As this carbon dioxide is absorbed by the ocean, excess carbonic acid is produced (Equation 5.3). Thus, human emissions of carbon dioxide, followed by absorption by the ocean, lead to changes in ocean chemistry, a process referred to as *ocean acidification*. As the ocean’s chemistry changes, the biology of the oceans can change – and given

human reliance on the oceans for food, this could lead to important impacts on humans. This will be discussed further in Chapter 9.

An emerging concern is whether the oceans and land biosphere can continue taking up as much carbon in the future as they are at present. It is unknown when or if we will reach a saturation point at which the reservoirs slow down or even cease their uptake. If that happens, then a higher fraction of emissions will remain in the atmosphere, and the abundance of carbon dioxide in our atmosphere will grow more rapidly. This leads to yet another worry for climate scientists: that climate change itself may alter the carbon cycle. In the next chapter, we will explore how such carbon cycle feedbacks may amplify climate change.

5.5 Some Commonly Asked Questions about the Carbon Cycle

Because of its central role in the climate change problem, climate skeptics occasionally challenge the claim that the increase in carbon dioxide since 1800 (Figure 5.6) is due to human activities. In this section I address this argument.

How do we know that combustion of fossil fuels is responsible for the increase in carbon dioxide, rather than non-human sources such as volcanoes or plants?

This is a reasonable question. After all, the amount of carbon dioxide absorbed by plants during the year and balanced by plant decay (approximately 110 GtC per year) is much larger than human emissions (around 11 GtC per year) – ditto for the ocean fluxes. So it may seem reasonable that the increase in atmospheric carbon dioxide might be driven by a slight excess of plant respiration over photosynthesis, or a slight excess flux of carbon dioxide out of the ocean. Similarly, we know that volcanoes emit carbon dioxide, and that over millions of years, volcanoes are a primary source of carbon dioxide in the atmosphere. So maybe the increase in atmospheric carbon dioxide is due to enhanced volcanic activity.

There are, however, several independent lines of evidence that unanimously agree that fossil fuel combustion is the dominant reason for the increase in atmospheric carbon dioxide over the past few centuries. First, Figure 5.7 shows that, for the past half-century, each year's increase in carbon dioxide in the atmosphere has been on average 44 percent of what humans released into the atmosphere in that same year. Thus, when humans were emitting smaller amounts of carbon dioxide in the 1960s, atmospheric carbon dioxide was increasing at a slower rate than when humans were dumping large amounts of carbon dioxide in the atmosphere, as we are today. If the source of carbon dioxide emissions were non-human, there is no reason that it would track human emissions of carbon dioxide so closely.

Second, the carbon dioxide can be chemically “fingerprinted” to show that it comes from fossil fuels. The method is based on *isotopes* of carbon. All carbon atoms have six protons, but carbon's isotopes have different numbers of neutrons. The most abundant

isotope is carbon-12, containing six neutrons to go with the six protons, and which makes up roughly 99 percent of the carbon on Earth. Carbon-13, with seven neutrons, makes up 1 percent of the carbon, and approximately one carbon atom out of a trillion is carbon-14, which has eight neutrons.

The chemical properties of an atom are for the most part set by the number of protons and electrons, so isotopes tend to have similar chemical properties. The chemistry, though, is not identical. Plants, for example, preferentially absorb carbon-12 when growing. And because fossil fuels are derived from plants, they reflect this preference. When the fossil fuels are burned, the carbon dioxide produced also reflects plants' preference for carbon-12 over carbon-13.

Scientists can measure the amount of carbon-12 and carbon-13 in atmospheric carbon dioxide, and those measurements show that the increase in atmospheric carbon dioxide over the past century is caused by carbon that is enhanced in carbon-12 – such as that which comes from plants. This allows us to rule out sources such as volcanoes or the ocean.

Thus, we know that the increase in atmospheric carbon dioxide is coming from plants, but is it coming from plants that died hundreds of millions of years ago (i.e., fossil fuels) or plants of today? To make that determination, we turn to carbon-14. Carbon-14 is produced in the atmosphere when a neutron created by a cosmic ray hits the nucleus of an atom of nitrogen-14. The nucleus absorbs the neutron and ejects a proton, thereby transforming itself into carbon-14. Carbon-14 atoms are incorporated into molecules of carbon dioxide and are then absorbed by plants and incorporated into plant material. If you walk outside and pull a leaf off a tree, a small fraction of atoms in that leaf would be carbon-14.

Carbon-14 is radioactive, meaning that its nucleus is unstable and reverts back to nitrogen-14 with a half-life of approximately 6,000 years (meaning that, after 6,000 years, half of the carbon-14 has converted back to nitrogen-14). To understand the implications of this, imagine a cotton plant that grew 6,000 years ago. As it grew, the plant absorbed carbon dioxide containing carbon-14 from the atmosphere, and the carbon-14 was incorporated into the plant. Immediately after the plant was picked, it would have the same proportion of carbon-14 as any living plant, and so would the cotton produced from it. But because it was no longer alive, it stopped absorbing carbon dioxide from the atmosphere. Over time, the amount of carbon-14 in the cotton slowly decreased as it was converted back to nitrogen-14.

Now imagine that modern-day archaeologists find a blanket made of this cotton and want to know how old it is. To do this, they measure the proportion of carbon-14 in the blanket and find that it has half the carbon-14 of a living plant. With a carbon-14 half-life of 6,000 years, the archaeologists conclude that the blanket is 6,000 years old. If they found that it had a quarter of the carbon-14 of a living plant, then it would be 12,000 years old. This process is known as *radiocarbon dating*.

Now let us turn our attention to fossil fuels. As we learned earlier, fossil fuels are produced when plant matter is buried for millions of years. After millions of years of being underground, all of the carbon-14 has converted back to nitrogen-14. Thus, fossil fuels contain no

carbon-14, a condition known as radiocarbon dead. So when the fossil fuels are burned, the carbon dioxide produced also has no carbon-14 in it. Scientists measuring the isotopic composition of atmospheric carbon dioxide have found that the carbon dioxide being added to the atmosphere is indeed mostly radiocarbon dead, showing that it is primarily coming from long-dead plants – fossil fuels – and not modern plants.

Putting all of the evidence together, along with an absence of any counterevidence, we see that there is no question that human activities are increasing the amount of carbon dioxide in the atmosphere. As my colleague John Nielsen-Gammon puts it, not only can we see the smoking gun, but the smoke is a chemical match to the gunpowder.

Why focus on carbon dioxide from fossil fuel combustion when plants and animals emit far more carbon dioxide to the atmosphere?

Humans, animals, bacteria, and plants do indeed emit enormous amounts of carbon dioxide to the atmosphere. As discussed earlier, the land biosphere emits 110 GtC per year, ten times present-day anthropogenic emissions. So why should we care about carbon dioxide from fossil fuels? To understand the answer, you need to understand the difference between carbon dioxide coming from fossil fuel combustion and from respiration by living organisms.

Let us begin by imagining that you plant a carrot seed, and over the next few months this seed grows into a carrot. As described by Equation 5.1, the plant grows by absorbing carbon dioxide directly from the atmosphere, and this reduces the amount of carbon dioxide in the atmosphere. Now let us imagine that the carrot is eaten by a goat. The goat metabolizes the carrot (in a manner approximately following Equation 5.2), which produces energy to power the goat's vital functions. The carbon dioxide produced is exhaled back into the atmosphere.

Thus, when an animal exhales carbon dioxide, it is releasing back into the atmosphere carbon dioxide that had been in the atmosphere just a few months before. Although this can lead to seasonal variations in carbon dioxide, as shown in Figure 5.1b, it does not cause long-term increases in carbon dioxide. Figure 5.6a confirms this by showing basically no change in carbon dioxide over the past 10,000 years – a period during which humans, plants, and animals were certainly releasing carbon dioxide to the atmosphere.

In contrast, when you burn fossil fuels, you are releasing to the atmosphere carbon that had been safely sequestered in rocks for hundreds of millions of years. This is a net addition to the atmosphere, so it does cause a long-term increase in carbon dioxide. Figure 5.6b confirms this: The increase in atmospheric carbon dioxide started with the industrial revolution, when society-wide burning of fossil fuels began.

5.6 The Long-term Fate of Carbon Dioxide

To get a feel for the long-term evolution of the climate over the next millennium, we need to know how long the carbon dioxide we release stays in the atmosphere. As a thought

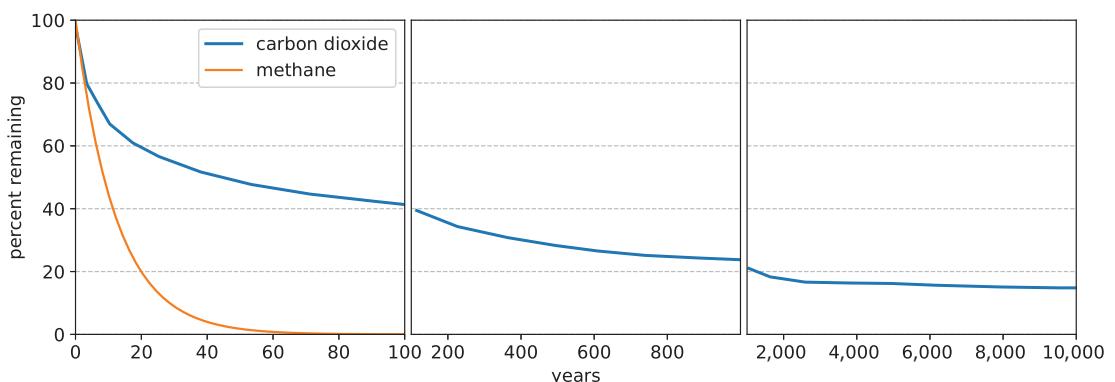


Figure 5.8 Fraction of carbon dioxide (blue) and methane (orange) remaining in the atmosphere after an initial pulse in year zero. The plot shows that it takes a very long time for carbon dioxide emitted to the atmosphere to be completely removed, whereas most of the methane is gone in a few decades. Carbon dioxide decay time is based on Figure 1 of Box 6.1 of Ciais et al. (2013). Methane decay time is based on an assumed lifetime of 12.4 years.

experiment, imagine that a pulse of carbon dioxide is instantaneously released into the atmosphere. At first, the land biosphere and mixed layer of the ocean rapidly remove carbon dioxide from the atmosphere – Figure 5.8 shows that about 50 percent of the carbon dioxide pulse is removed in 50 years.

Removing additional carbon dioxide requires transport into the deep ocean, which is a slower process. After 500 years, about 28 percent of the carbon dioxide pulse remains in the atmosphere. At this point, the deep ocean is in equilibrium with the atmosphere and cannot absorb any more carbon. Further removal of carbon dioxide requires reactions that transfer carbon between the ocean and rock reservoirs. But this process is very slow. After 10,000 years, 14 percent of the initial pulse of carbon dioxide is still in the atmosphere. The last 14 percent takes even longer to remove – a hundred thousand years or so.

The very long time it takes for carbon to be removed from the atmosphere is confirmed by measurements of carbon dioxide during the Paleocene–Eocene Thermal Maximum (discussed in Section 2.3.2; see Figure 2.11). This is an event about 55 million years ago when a huge pulse of carbon (several thousand GtC) was released into the atmosphere, leading to a sudden and significant warming of the planet. It took hundreds of thousands of years for that slug of carbon to be removed and for the warming it caused to dissipate.

While there are multiple time scales involved in the removal of carbon dioxide from the atmosphere, it's often useful to think of a single characteristic lifetime for carbon dioxide. If one uses the time to remove 70 percent of the carbon dioxide from the atmosphere, one gets a lifetime for carbon dioxide added to the atmosphere of around 500 years. Note that we're not talking about the lifetime of actual carbon dioxide molecules here — earlier in this chapter, we talked about how all of the carbon is cycled from the atmosphere and into the land biosphere or ocean in just a few years. Rather, we're talking about the lifetime of

a perturbation to atmospheric carbon dioxide. If one increases the amount of carbon dioxide in the atmosphere by some amount, as we hypothesized in Figure 5.8, it takes a very long time for the atmospheric abundance to return to the value before the perturbation.

The upshot is that, if you drive your car to go grocery shopping this afternoon, the increase in atmospheric carbon dioxide caused by this will remain for a very long time. Some of it will still be around in 10,000 years, along with the warming it caused. We will revisit the grim implications of this in Chapter 8, but it is important to understand that actions we take today will reverberate for tens of thousands of years. If we fail to solve the climate problem, what will people living in the years 3000, 4000, or 10 000 AD think of us?

5.7 Methane

Most discussions of climate change and greenhouse gases focus on carbon dioxide. This is appropriate since, as we'll see in Chapters 6 and 8, carbon dioxide is by far the main driver of climate change. However, the other greenhouse gases play an important role. In this section, I will discuss methane, also known as natural gas, which is another significant greenhouse gas.

Methane is roughly 32 times more powerful than carbon dioxide per kilogram – meaning that it takes 32 kilograms of carbon dioxide to equal the warming from one kilogram of methane. This warming power relative to carbon dioxide is known as the *global warming potential*. Table 5.1 lists several important greenhouse gases and their global warming potential.

Methane has increased from 0.8 ppm in the pre-industrial atmosphere to about 1.9 ppm today — an increase of 1.1 ppm. Accounting for the global warming potential of 32, this increase in methane is equal to about a 30-ppm increase in carbon dioxide. Carbon dioxide has increased by 130 ppm since pre-industrial times, so this increase in methane since pre-industrial times provides about one-quarter of the global warming power of the increase in carbon dioxide. We'll discuss this more quantitatively in the next chapter.

Table 5.1 Greenhouse-gas metrics

Species	Lifetime	Global warming potential	Increase in abundance since pre-industrial times
Carbon dioxide	500 years	1	130 ppm
Methane	12.4 years	32	1.1 ppm
Nitrous oxide	109 years	260	75 ppb
Halocarbons	Years to millennia	100s to 1,000s	

ppb, parts per billion

Methane is emitted to the atmosphere from both human and natural processes. About 60 percent of human methane emissions are from agriculture and waste. Livestock is the largest source of methane in this category. Cattle, as well as goats and sheep, are ruminants, and these animals produce methane in their guts during the digestion of food. This methane is eventually released to the atmosphere (out of both ends of the animals). The next largest source in this category is bacterial processes in landfills and other waste repositories. Emissions from rice paddies are a third significant source. In the warm and wet environment of a flooded rice field, bacteria in the soil efficiently produce methane, the vast majority of which is then released to the atmosphere.

The release of methane from the petrochemical industry is responsible for about 30 percent of human emissions of methane. This comes from leakage of methane from natural gas wells as well as release of geologic methane from coalmines. Finally, burning of forest and other biomass primarily produces carbon dioxide, but it also produces methane if the combustion temperature is sufficiently low (e.g., a smoldering fire). This is responsible for the remaining 10 percent of human methane emissions.

During the 2000s, methane emissions from natural sources were about equal to human emissions. Approximately two-thirds of these natural emissions were from natural wetlands, which produce methane the same way that flooded rice paddies do. Minor contributions came from the ocean, from freshwater lakes and rivers, and from wild animals, particularly termites.

Besides differences in global warming potential, the different gases also have different lifetimes, which are also listed in Table 5.1. Methane, for example, is removed from the atmosphere by oxidation, which follows the following schematic reaction, which is similar to the respiration reaction (Equation 5.2) and the fossil fuel combustion reaction (Equation 5.6):



On average, a molecule of methane is destroyed by this reaction 12.4 years after it was emitted. If we stopped emitting methane today, all of the human-emitted methane would be gone in a few decades (Figure 5.8) and the atmospheric abundance would be back down to pre-industrial amounts. This is much shorter than the time it takes to remove carbon dioxide from the atmosphere.

5.8 Other Greenhouse Gases

The most powerful greenhouse gases on a per molecule basis are the halocarbons, which are 100 percent human-made and emitted in a variety of industrial processes. While there are many different chemicals that fall into this category, and these have different chemical properties, in general one halocarbon molecule equals hundreds or thousands of carbon dioxide molecules – so despite being about 1/10,000 as abundant as carbon dioxide, even the

small part-per-billion increases in these halocarbons make an important contribution to the greenhouse effect.

Ozone is not listed because its lifetime in the atmosphere is so short (weeks to months) that it is difficult to compare it to carbon dioxide using metrics in Table 5.1. Ozone is not emitted by human activities directly. Rather, humans emit the precursors, mainly oxides of nitrogen and volatile organics, and these react in the atmosphere to produce ozone. Despite these differences, ozone is also an important global warming agent.

Overall, the biggest contribution to global warming comes from carbon dioxide. And since most of this comes from fossil fuel combustion, this is why so much of the climate debate revolves around energy and how we produce it. That said, the other gases in the table are also clearly important.

These differences in lifetime have important implications when designing policies to address climate change. If we stopped emitting carbon dioxide today, the atmospheric abundance would decline slowly over the next few centuries, and this means that the warming would also persist for a very long time. But policies to address methane would lead, within a few decades, to significant reductions in atmospheric methane and a corresponding cooling of the climate system.

It is also clear that halocarbons are an important gas to focus on. Their atmospheric abundance is small, but the combination of very long lifetimes and high global warming potential means that, if we foolishly emit a lot of them, they could significantly alter our climate. Luckily, as we'll talk about in Chapter 13, many of these gases, particularly those that also deplete stratospheric ozone, are already being phased out.

5.9 Chapter Summary

- Greenhouse gases are the components of our atmosphere that absorb infrared photons. The three most important are (in order) water vapor, carbon dioxide, and methane. Nitrogen, oxygen, and argon, which make up approximately 99.9 percent of the dry atmosphere, are not greenhouse gases.
- While water vapor is the most important greenhouse gas in our climate system, carbon dioxide is the most important one for the problem of human-induced climate change.
- The carbon cycle describes how carbon cycles through its primary reservoirs: the atmosphere (containing 864 GtC), land biosphere (2,150 GtC), ocean (900 GtC in the mixed layer and 37,100 GtC in the deep ocean), and rocks (millions and millions of GtC).
- The atmosphere exchanges carbon with the land biosphere through photosynthesis and respiration. The atmosphere exchanges carbon with the ocean when carbon dioxide dissolves into or is emitted from the ocean. Over the course of several centuries, a carbon atom added to the atmosphere will cycle through all of the other reservoirs and return to the atmosphere.
- The atmosphere–land biosphere–ocean system also exchanges carbon with rock reservoirs through volcanism and chemical weathering. This exchange is extremely slow.

- Humans are perturbing the carbon cycle mainly by extracting and burning fossil fuels. The result is the creation of a new, rapid pathway moving carbon from rocks to the atmosphere. Between 2008 and 2017, fossil fuel combustion released an average of 9.5 GtC to the atmosphere from the rock reservoir, which is about 100 times the amount released from the rocks naturally. Land-use change is another important human source, releasing 1.5 GtC per year from the land biosphere into the atmosphere during this period.
- This has increased atmospheric carbon dioxide abundance from approximately 280 ppm in 1750, before the industrial revolution, to 412 ppm in 2020.
- It takes a long time for the carbon cycle to remove carbon that humans add to the atmosphere. About 50 percent of it is removed in a few decades, 75 percent in a few centuries, and the last 25 percent is removed over a hundred thousand years. This means that atmospheric carbon dioxide will be elevated by human activities for a very long time – even if we stop burning fossil fuels in the next few decades. If you want a single lifetime for carbon dioxide, a value of 500 years is a good one to use.
- Greenhouse gases besides carbon dioxide can also be important. Many of them are much more powerful on a per-molecule basis. One kilogram of methane, for example, has the warming power as 32 kilograms of carbon dioxide. Since before the industrial revolution, methane has increased from 0.8 ppm to 1.9 ppm, an increase of 1.1 ppm, which has the warming equivalent of an increase of about 30 ppm of carbon dioxide.
- Methane has a short lifetime of 12.4 years, so if we can reduce emissions, the atmospheric abundance of methane will decline significantly within a few decades.

See www.andrewdessler.com/chapter5 for additional resources for this chapter.

TERMS

Carbon cycle
Carbonic acid
Chemical weathering
Deep ocean
Deforestation
Fossil fuels
Global warming potential
Greenhouse gas
Halocarbons
Isotopes
Keeling curve
Land-use changes
Mixed layer
Ocean acidification
Parts per million
Photosynthesis

Radiocarbon dating
Respiration
Turnover time

PROBLEMS

1. (a) Describe the processes that transfer carbon from the atmosphere to the land, and from the land to the atmosphere. What are the chemical reactions that describe these processes?
(b) How do these processes interact to produce the “sawtooth” annual cycle in the atmospheric abundance of CO₂ shown in Figure 5.1a?
2. A letter to the editor of the *Austin American-Statesman*, published on December 23, 2009, asks this question: “The trillion-dollar question that Copenhagen has not answered [is this]: Because carbon dioxide molecules are all identical, why is it that carbon dioxide from carbonated beverages, pets, cattle, farm animals, and humans, yeast, dry ice, fireplaces, charcoal grills, campfires, wildfires, alcohol and ethanol is good, and carbon dioxide from fossil fuel is bad? Can anyone in the United States answer this question?” What is your answer?
3. Your aunt asks you how we know that volcanoes are not responsible for the observed increase in carbon dioxide. What do you tell her?
4. Explain how isotopes help us identify human activities as the reason atmospheric carbon dioxide is increasing.
5. Your grandfather asks you to explain how humans are modifying the carbon cycle. What do you tell him?
6. Explain how “chemical weathering” removes carbon dioxide from the atmosphere. What is the weathering chemical reaction? Can this process play an important role in counter-acting the increase in atmospheric carbon dioxide caused by humans?
7. Of the carbon dioxide humans add to the climate, approximately half is removed within a few decades. Where does it go? How would it affect the climate if, all of a sudden, all of the carbon dioxide we emit stayed in the atmosphere?
8. Why is rain naturally acidic? What then, does the term *acid rain* refer to? (Acid rain is not covered in the chapter, so you will have to do some outside research on it.)
9. The sawtooth in the carbon dioxide time series due to the annual cycle in northern hemisphere plant growth is dramatic. The data in Figure 5.1 come from Mauna Loa, in Hawaii. Based on the material in this chapter, predict how the magnitude of this annual cycle in the Arctic would compare to that in the Antarctic. Find the data online (link to data located at www.andrewdessler.com/data) and see if you can confirm your hypothesis.

6

Forcing, Feedbacks, and Climate Sensitivity

In Chapter 4, we showed that the temperature of a planet is a function of the solar constant, the albedo of the planet, and the composition of the atmosphere (Equation 4.5). In Chapter 5, we showed that humans are altering the composition of the atmosphere by adding greenhouse gases to it, thereby increasing the number of layers, so we would expect the planet's temperature to be increasing. In Chapter 2, we showed that temperature is indeed going up. If that were all there was to climate change, we would be done with the science. But, as we'll talk about in this chapter, there is more interesting physics that we have to consider to fully understand the evolution and magnitude of modern climate change.

6.1 Time Lags in the Climate System

All of the climate calculations in Chapter 4 were equilibrium situations in which we explicitly assume that E_{in} and E_{out} are equal. But modern climate change is not an equilibrium problem. To understand what I mean by this, consider a planet with no atmosphere that is in equilibrium, so that *energy in* equals *energy out*. Assuming the planet is Earth-like (so $E_{\text{in}} = E_{\text{out}} = 238 \text{ W/m}^2$), we calculated in Chapter 4 that the planet's surface temperature would be 255 K. The energy fluxes for this planet are shown in Figure 6.1a.

Now let us imagine that a one-layer atmosphere is instantly added to the planet. What are the fluxes the instant after the layer is added? The temperature of the surface is still 255 K because objects have thermal inertia, which prevents their temperatures from changing instantly, just like a pot of water you put on the stove does not immediately boil. This means that the instant after the atmosphere is added, the surface is still 255 K and is still emitting exactly the same as it was before the atmosphere was added, 238 W/m^2 .

The atmosphere, however, is now absorbing all of the photons coming from the surface. Half of the absorbed energy is re-emitted upward to space, and half is re-emitted downward back to the surface.¹ This is shown in Figure 6.1b. So E_{in} for the planet remains at 238 W/m^2 , but the planet's E_{out} has dropped to 119 W/m^2 . Because E_{in} for the planet now exceeds E_{out} , the planet is accumulating energy and begins warming.

How fast does the planet warm in response to an energy imbalance? This is set by the heat capacity of our massive ocean, which covers 70 percent of the surface to an average depth of

¹ I am implicitly assuming here that *energy in* always equals *energy out* for the atmosphere. In more technical terms, this means that the heat capacity of the atmosphere is zero. This is not a bad assumption because, while not zero, the heat capacity of the atmosphere is indeed much smaller than the heat capacity of the rest of the climate system.

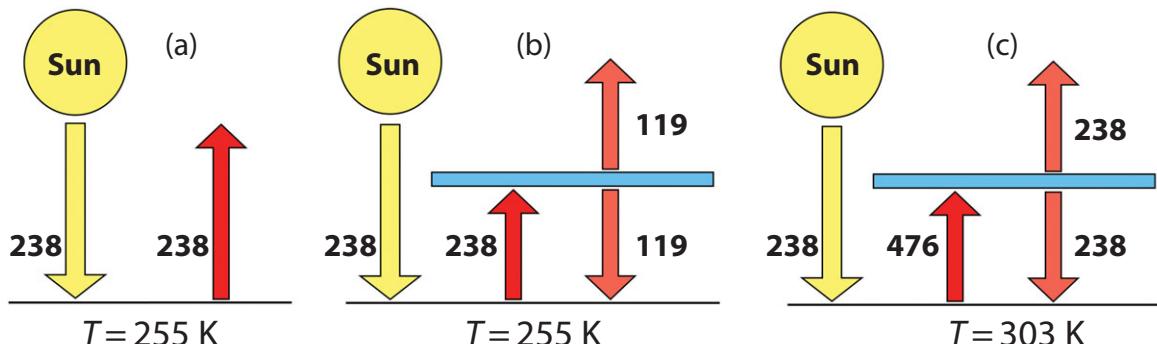


Figure 6.1 Schematic of energy fluxes on a planet (a) with no atmosphere, (b) the instant after a one-layer atmosphere is added to the planet, and (c) after the climate reaches its new equilibrium.

4,000 meters (2.5 miles). However, as in Chapter 5, you shouldn't think of the ocean as a single entity, but rather think of it split into two parts: a mixed layer on top, about 100 meters thick, which communicates rapidly with the atmosphere, and the deep ocean containing the other 97 percent of the ocean's mass, which communicates slowly with the atmosphere.

Figure 6.2a shows the temperature of the planet over time. When the atmosphere is instantaneously added at Year 0, the planet begins rapidly warming for about 20 years, which represents warming of the ocean's mixed layer. Because its mass is relatively small (compared to the mass of the entire ocean), this warming is fast. Warming after year 20 requires heating of the deep ocean. The deep ocean contains most of the mass of the ocean, so the warming rate is slow. It takes millennia for the deep ocean to reach equilibrium and the planet to cease warming.

The time series of *energy out* is shown in Figure 6.2b. Prior to year 0, *energy out* is 238 W/m^2 . As discussed above, the addition of the layer at year 0 causes E_{out} for the planet to drop immediately, from 238 W/m^2 to 119 W/m^2 . Because *energy in* does not change, this creates an energy imbalance (corresponding to the situation in Figure 6.1b), which causes warming after year 0 in Figure 6.2a.

As the planet heats up, *energy out* increases, as seen in Figure 6.2b. This occurs simply because, as we discussed in Chapter 3, warmer objects radiate more blackbody energy. Eventually, after many millennia, E_{out} reaches 238 W/m^2 , at which point E_{in} and E_{out} balance, and the planet reaches a new equilibrium – but at a warmer temperature. This situation is shown schematically in Figure 6.1c.

The scenario just described is basically what happens when greenhouse gases are added to our atmosphere. The greenhouse gases intercept some of the energy escaping to space and redirect it back toward the surface. In so doing, greenhouse gases knock the system out of equilibrium and force the climate system to warm. The planet warms until *energy out* again balances *energy in* for the planet as a whole and for each individual component of the climate system.

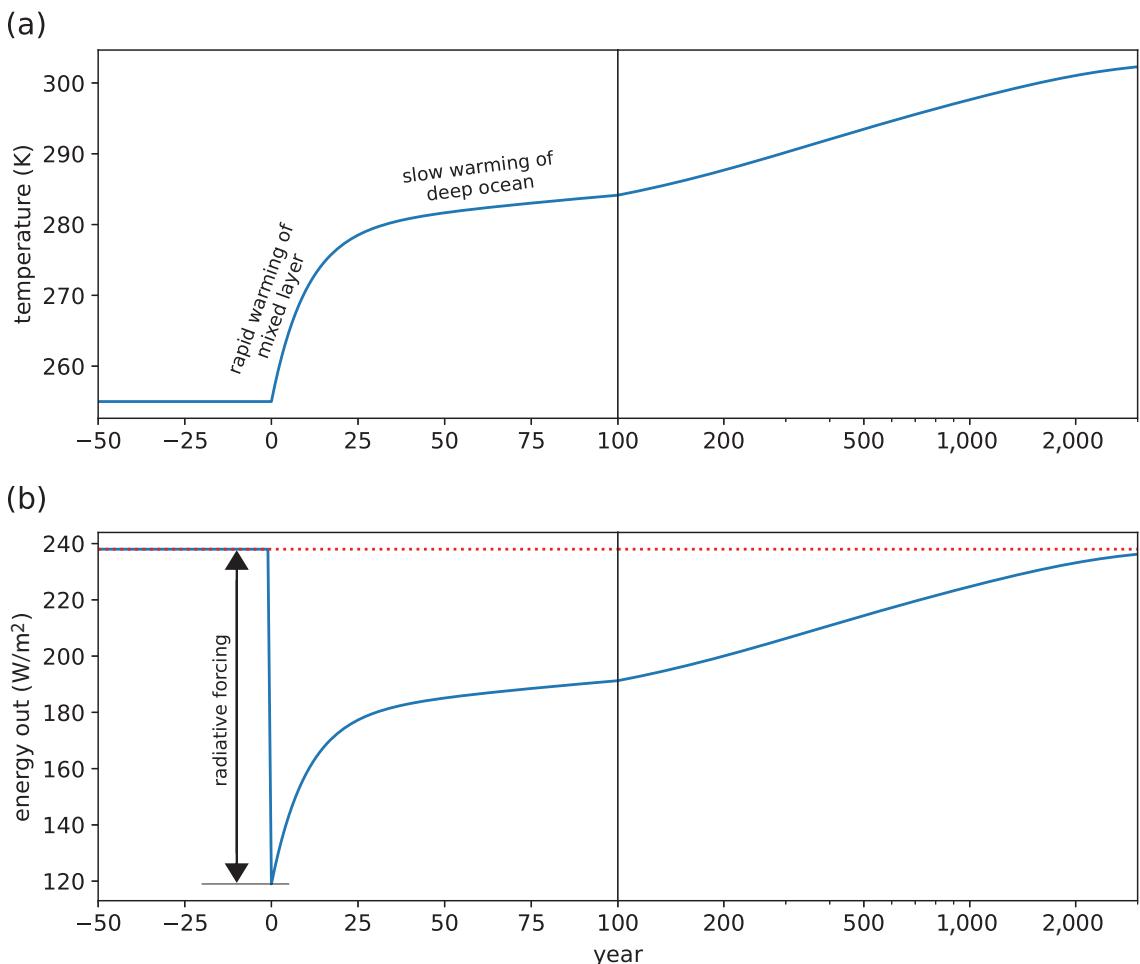


Figure 6.2 (a) Plot of temperature for the planet shown in Figure 6.1 as a function of time, (b) plot of E_{out} for the planet. A one-layer atmosphere is added instantaneously in year 0, and E_{in} for the planet remains constant at 238 W/m^2 (the dotted red line in panel b).

Viewed this way, one can think of climate change as the way the planet restores energy balance after that energy balance is perturbed. In the next section, I will quantify how much humans have perturbed the planet's energy balance, thereby causing modern climate change.

6.2 Radiative Forcing

The discussion in the last section leads us to one of the most important concepts in climate science: *radiative forcing*. Radiative forcing (often abbreviated RF) is the change in $E_{\text{in}} - E_{\text{out}}$ for the planet as a result of some change imposed on the planet *before the temperature of the planet has adjusted in response*:

$$RF = \Delta(E_{in} - E_{out}) = \Delta E_{in} - \Delta E_{out} \quad (6.1)$$

In the example just given, ΔE_{out} is -119 W/m^2 ; that is the change in E_{out} the instant after the atmosphere is added but before the warming temperature has caused E_{out} to increase (indicated by the arrow in Figure 6.2b). Note that ΔE_{in} is zero because *energy in* does not change when an atmospheric layer is added. Thus, the radiative forcing of adding a one-layer atmosphere is $0 - (-119) = +119 \text{ W/m}^2$. The sign convention is that positive radiative forcings correspond to changes that warm the climate, whereas negative ones correspond to changes that cool the climate.

Example 6.1: What is the radiative forcing of a 5 percent increase in solar constant for the Earth that occurs over 100 years?

Let us begin by calculating ΔE_{in} , the change in *energy in*. From Chapter 4, we know that $E_{in} = S(1 - \alpha)/4$, which for the Earth is 238 W/m^2 . If the solar constant S increased by 5 percent, then S would increase to $1,360(1.05) = 1,428 \text{ W/m}^2$. For this new value of the solar constant, $E_{in} = 250 \text{ W/m}^2$. Thus, E_{in} has increased from 238 W/m^2 to 250 W/m^2 , so $\Delta E_{in} = +12 \text{ W/m}^2$.

What is ΔE_{out} for this solar constant change? E_{out} is determined entirely by atmospheric composition (i.e., number of layers) and temperature. Atmospheric composition is not changing in this example, and radiative forcing is defined as the response to an instantaneous change, before the temperature of the planet has adjusted to the change. Thus, E_{out} does not change and $\Delta E_{out} = 0$. Putting it together using Equation 6.1, we find that the radiative forcing for this change in the solar constant is $+12 \text{ W/m}^2$.

The fact that the change occurred over the course of 100 years does not enter into the calculation. Radiative forcing calculations are done under the assumption that the climate is not allowed to respond to the change, so the length of time the change is imposed over is irrelevant.

The imposition of a radiative forcing on a planet, such as a change in solar constant, will take the planet out of energy balance – so that E_{in} and E_{out} are no longer equal to each other. In response, the temperature of the planet will adjust so that E_{in} once again equals E_{out} , as we discussed in the last section. In the case of an increasing solar constant, the planet will warm, increasing E_{out} , until E_{in} and E_{out} are once again in balance.

Radiative forcing is a quantitative measure of how much some perturbation (e.g., an increase in solar constant, increase in greenhouse gases) will change the climate. The advantage of using radiative forcing is that it allows us to express diverse changes to the climate system using a common metric. For example, it allows us to quantitatively compare the climate-changing effect of a 100-ppm increase in carbon dioxide to a 1 percent increase in the solar constant. Correspondingly, radiative forcing of $+1 \text{ W/m}^2$ will produce similar warming of the climate, regardless of whether that change was caused by a brightening of the Sun, an increase in carbon dioxide, an increase in methane, or some other change.

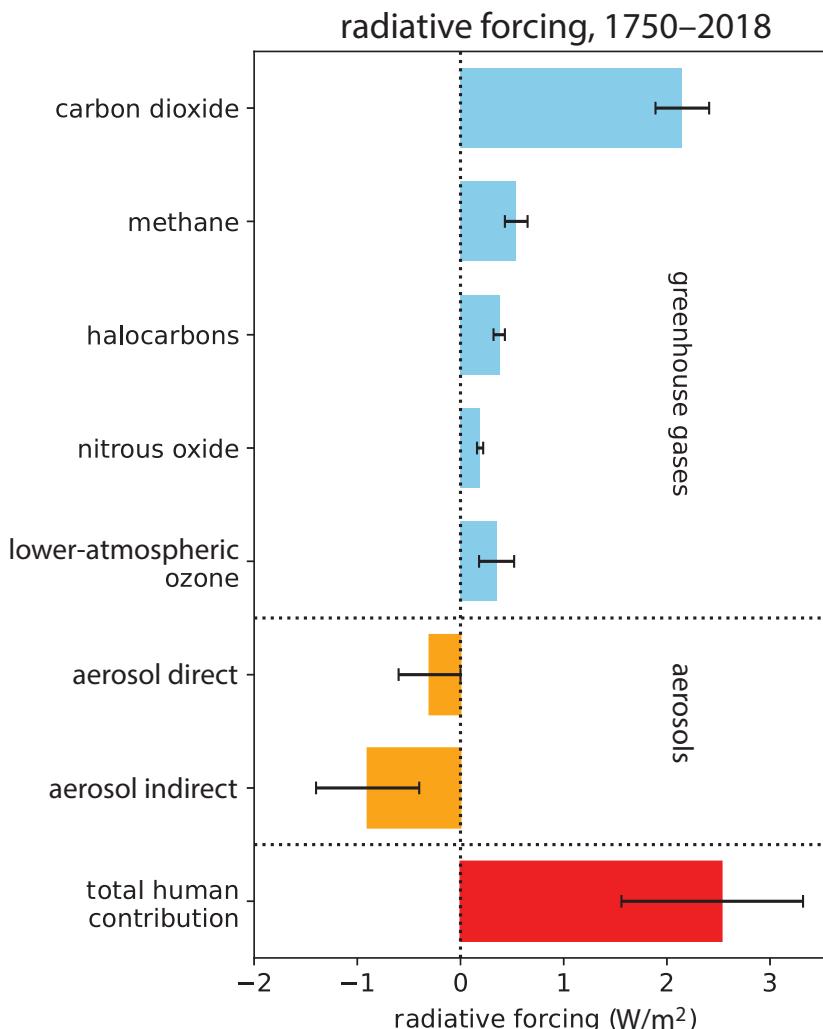


Figure 6.3 Radiative forcing caused by human activities between 1750 and 2018. The error bars indicate the uncertainty of the estimate.

Figure 6.3 shows the major radiative forcings that have influenced our climate over the past few centuries. In much the same way that temperature anomalies are the change in temperature from a reference period, radiative forcings are the changes in E_{in} and E_{out} relative to a reference climate. The values in Figure 6.3 are radiative forcing relative to 1750, which is considered the pre-industrial climate. Almost all of the radiative forcings in Figure 6.3 are the result of human activities. In the rest of this section, I describe each one of these factors.

6.2.1 Greenhouse Gases

The atmospheric abundance of carbon dioxide increased from 280 to 407 ppm between 1750 and 2018; this corresponds to a radiative forcing of $+2.2 \text{ W/m}^2$. Because of the long

lifetime of carbon dioxide in our atmosphere (many centuries), a fraction of the radiative forcing from carbon dioxide the Earth is experiencing right now is due to carbon dioxide emitted in the early 1800s.

Increases in methane, nitrous oxide, and the halocarbons between 1750 and 2018 produced radiative forcings of $+0.54$, $+0.19$, and $+0.38 \text{ W/m}^2$, respectively. Ozone in the lower atmosphere is both a greenhouse gas and one of the primary components of photochemical smog. As the world has become more industrialized, lower atmospheric ozone has increased along with the other components of air pollution. This increase contributes a positive radiative forcing of $+0.35 \text{ W/m}^2$. Ozone in the stratosphere, in contrast, has been declining as a result of ozone depletion caused by halocarbons. This contributes a negative radiative forcing of -0.05 W/m^2 (not shown in Figure 6.3).

Virtually all of these changes in these greenhouse gases were due to human activities. Together, they imposed a radiative forcing of $+3.5 \text{ W/m}^2$ between 1750 and 2018. Carbon dioxide contributed about 60 percent of this, so it was the single most important greenhouse gas emitted by human activities. But the combined radiative forcing from the other greenhouse gases was also important.

Lastly, there's one more number that it's good to remember: radiative forcing from doubled carbon dioxide. If carbon dioxide in our atmosphere doubled, the radiative forcing would be $+4 \text{ W/m}^2$. This turns out to be a benchmark that's frequently used in climate science, and we will use this later in the chapter when we introduce the concept of climate sensitivity.

6.2.2 Aerosols

Aerosols are particles so small that they do not fall under the force of gravity but remain suspended in the atmosphere for days or weeks. Aerosols can affect planetary energy balance, thereby altering the climate. There are several types of aerosols, and their composition determines how they affect E_{in} and E_{out} .

When fossil fuels containing sulfur impurities are burned, the sulfur is released to the atmosphere with the other products of combustion. Sulfur is also released into the atmosphere during biomass burning and from natural processes in the ocean. Once in the atmosphere, the sulfur gases react with other atmospheric constituents to form small liquid droplets, known as sulfate aerosols.

Sulfate aerosols are highly reflective and reflect incoming solar radiation back to space, so their net effect is to cool the climate. As a result of human activities over the past two centuries, the abundance of sulfate aerosols has increased and this generates a negative radiative forcing, which has tended to cool the climate.

These sulfate aerosols exist in the lower atmosphere, so their lifetime is short – after the aerosols form, it takes just a few weeks before they are either washed out of the atmosphere by rain or fall to the ground. This means that the radiative forcing the Earth is experiencing at any given time from these aerosols is due entirely to emissions that occurred in the past month or two. This should be contrasted with carbon dioxide, which stays in the atmosphere for centuries.

Another important – but episodic – source of sulfur gases for the atmosphere is volcanic eruptions. Volcanoes emit enormous amounts of sulfur gas, and energetic eruptions can inject it directly into the stratosphere. Aerosols in the stratosphere can remain there for several years, much longer than an aerosol resides in the lower atmosphere. This long lifetime, combined with the massive amounts of sulfur released, means that a single volcano can produce a negative radiative forcing of several watts per square meter that lasts for several years after the eruption (Figure 6.4).

This negative radiative forcing can lead to a noticeable cooling of the climate following an eruption. In 1816, for example, after three major eruptions in three years, the United States and Europe experienced the “year without a summer,” in which snow fell in Vermont in June, and heavy summer frosts caused crop failures and widespread food shortages. When that summer was followed by a winter so cold that the mercury in thermometers froze (this happens at -40°C), many residents fled the northeast United States and moved south.

A few years after a volcanic eruption, volcanic aerosols fall out of the stratosphere and the climate warms back up. Combined with the fact that such massive volcanic eruptions occur infrequently (as we can see in Figure 6.4), the long-term impact of volcanoes on the climate has been relatively small over the past 150 years.

Black carbon aerosols, such as soot, are another important aerosol type. This type of aerosol is produced by incomplete combustion, such as a smoldering fire or by two-stroke gasoline engines, so they are frequently of human origin. Because they are dark, they absorb solar radiation and decrease the planet’s albedo, thereby warming the planet. Over the past few centuries, black carbon aerosol abundance has increased as more people burn more stuff, leading to a positive radiative forcing. Much like sulfate aerosols, these black carbon aerosols typically have atmospheric lifetimes of a few weeks.

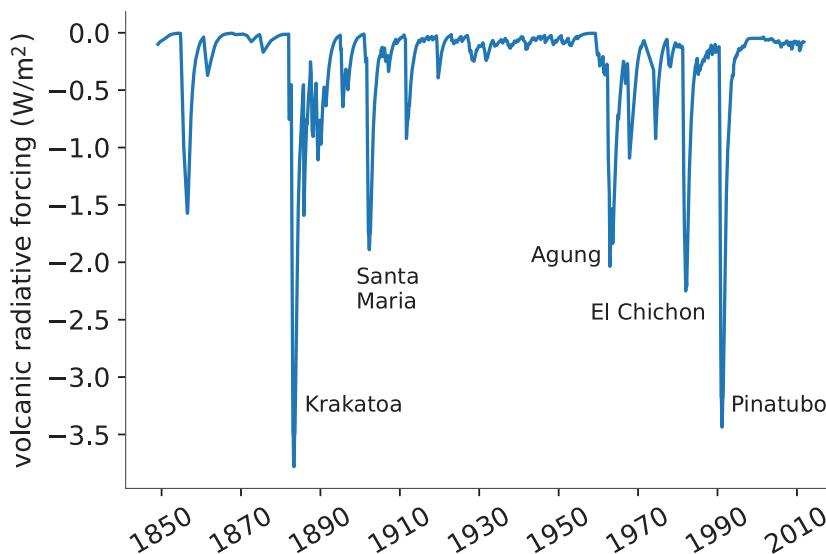


Figure 6.4 Radiative forcing (W/m^2) from volcanic aerosol. These estimates were obtained from NASA GISS; <https://data.giss.nasa.gov/modelforce/strataer/>, retrieved October 14, 2020.

Another type of aerosol is mineral dust. Most of this dust comes from natural processes, such as dust picked up off the world's deserts by strong winds. But approximately 20 percent of mineral dust comes from anthropogenic sources – mainly agricultural practices (e.g., harvesting, plowing, overgrazing), changes in surface water features (e.g., drying out of lakes such as the Aral Sea and Owens Lake), and industrial practices (e.g., cement production, transport). The net effect of dust is to cool the planet. Like other types of aerosols, these dust aerosols have atmospheric lifetimes of a few weeks.

Overall, humans have caused the amount of aerosol in the atmosphere to increase. Combining all types of aerosols (those discussed earlier as well as several not discussed), the direct radiative effect of aerosols is to cool the climate, with an estimated negative radiative forcing of about -0.3 W/m^2 . This is known as the *aerosol direct effect*.

In addition to this direct cooling effect, aerosols also have an indirect effect on the climate by altering clouds. There are several ways that this can occur. One of the clearest mechanisms is by increasing the number of particles in a cloud. Cloud particles generally form when water condenses onto *cloud-condensation nuclei*, or CCN, which are small hydrophilic aerosols, meaning that they attract water. If you go outside and look at a cloud, at the center of each cloud droplet is a CCN. In fact, it is the number of CCN that determines how many cloud droplets are found in a cloud.

Aerosols can act as CCN, so if you add aerosols to a cloud, you increase the number of CCN. This leads to an increase in the number of droplets making up the cloud. But the total liquid water contained in the cloud is more or less fixed. Thus, the increase in the number of droplets means that each droplet has less water and is therefore smaller. This is akin to cutting a pie into more slices: The total amount of pie is fixed, so more slices means that each slice must be smaller. This situation is shown in Figure 6.5.

It turns out that a cloud containing smaller droplets is more reflective than one containing large droplets. A familiar example of this can be seen in your kitchen in the difference between regular table sugar and powdered sugar. Chemically, the two substances are identical, but powdered sugar is made up of much smaller particles. Because smaller particles tend to be more reflective, the pile of powdered sugar is a brighter white than a pile of table sugar.

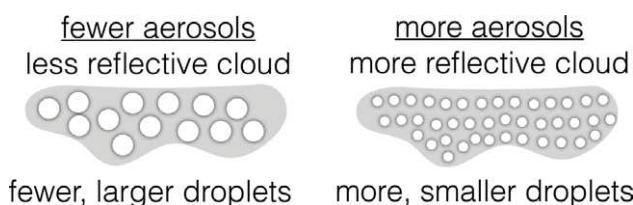


Figure 6.5 Schematic of how aerosols affect clouds. The cloud on the left developed in a low-aerosol environment, so the cloud particles are relatively large. The cloud on the right developed in an environment in which humans have added aerosols to the atmosphere. The increased abundance of aerosols generates a cloud comprised of a larger number of smaller particles. This means the cloud on the right reflects more sunlight back to space than the cloud on the left.

Thus, as human activities add aerosols to the atmosphere, some of these are entrained in clouds, making the clouds brighter and more reflective. This can be seen in what are called *ship tracks*. The exhaust from diesel engines contains fine particulates that can serve as CCN. As ships steam across the ocean, these fine aerosol particles from their engines are transported by the winds into low-level clouds, leading to increases in numbers of droplets and brighter clouds. These can be seen from a satellite (Figure 6.6) as lines of bright clouds tracing the paths of these ships.

This effect on cloud reflectivity is just one way in which aerosols affect clouds. By making the cloud particles smaller, aerosols also slow down the coagulation process whereby cloud droplets combine to form raindrops. This reduces rainfall from a cloud, so the clouds last longer. Aerosols can also change the height of the cloud, as well as the phase (ice versus liquid). The addition of black carbon to clouds can lead to local warming that can cause clouds to evaporate.

Taken together, the impact of aerosols on clouds, known as the *aerosol indirect effect*, produces a negative radiative forcing of between -1.4 W/m^2 and -0.4 W/m^2 , with a best-guess estimate of -0.9 W/m^2 . Combining the direct and indirect effects, aerosols produce a total negative radiative forcing of roughly -1.1 W/m^2 .

Because aerosols last only a few weeks in the atmosphere before they are removed, they do not have time to become well mixed throughout the atmosphere (which takes a year or so). As a result, the distribution of aerosols in our atmosphere is highly variable, with most aerosols found near their sources. Figure 6.7 shows their distribution, and from this we can infer the major sources of aerosols across the globe: Saharan dust that is blown westward from North Africa into the Atlantic, smoke from biomass burning over central Africa, and an aerosol soup sitting over Asia.

It is also apparent that aggressive air-pollution control efforts in the United States and Western Europe have worked – these regions have low levels of aerosol abundance despite

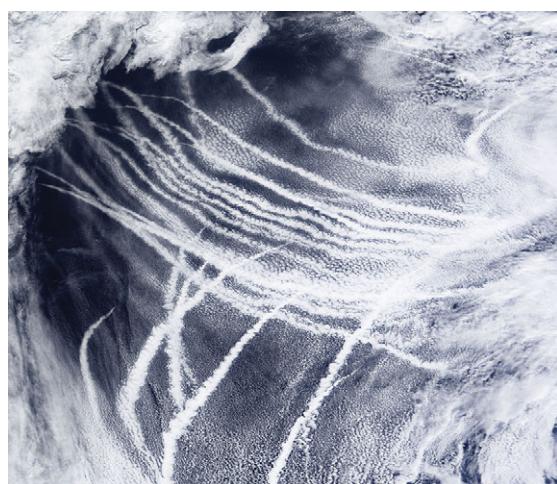


Figure 6.6 Ship tracks in clouds off the West Coast of the United States (image obtained from the Earth Observatory, <https://earthobservatory.nasa.gov/images/37455/ship-tracks-south-of-alaska>).

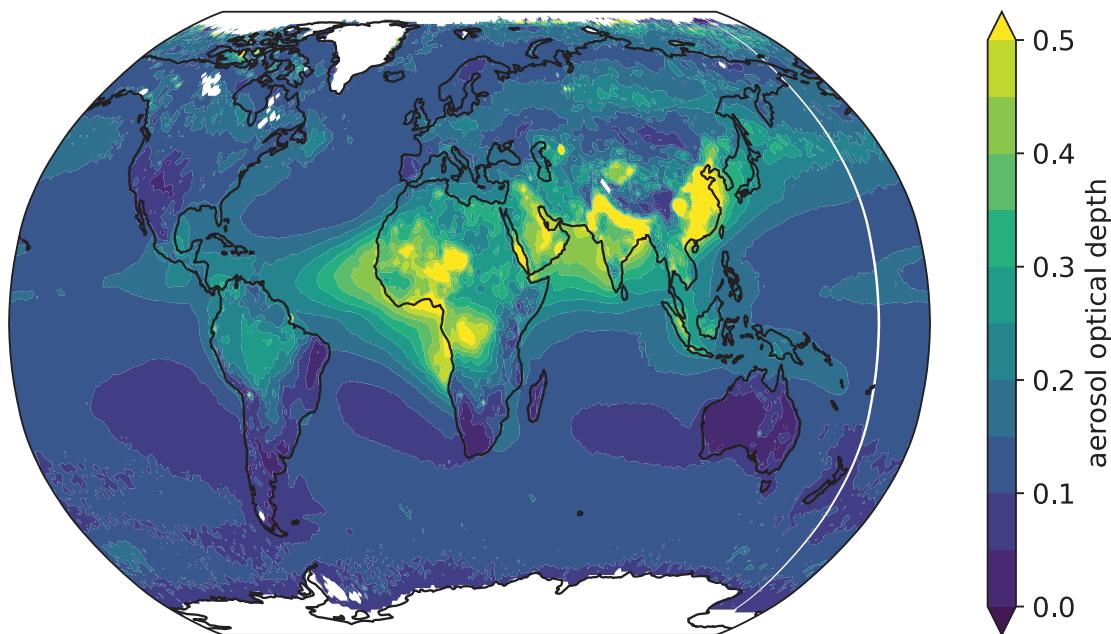


Figure 6.7 Global map of annual average aerosol optical depth (a measure of the abundance of aerosols) for the years 2005–2019. White areas denote regions where no data were obtained. Data are the MYD08 monthly aerosol fields from the Moderate Resolution Imaging Spectroradiometer onboard NASA’s Aqua satellite. This plot was produced on May 25, 2020, using the Giovanni online data system (<https://giovanni.gsfc.nasa.gov/giovanni/>), developed and maintained by the NASA GES DISC.

large economies. It is the countries with laxer environmental regulations, such as China and India, that are responsible for much of the anthropogenic aerosols in the atmosphere.

So although the global average radiative forcing from aerosols is -1.1 W/m^2 , this is not evenly distributed over the globe. In regions where aerosol abundance is high, aerosols can have a local radiative forcing of many times this value, whereas in regions that have low aerosol abundance, the local radiative forcing can be near zero. This can be contrasted to greenhouse gases such as carbon dioxide or methane, which are well mixed in the atmosphere because of their long atmospheric lifetimes (many years), resulting in a radiative forcing evenly distributed across the globe.

From a global average perspective, the negative radiative forcing from aerosols offsets about 30 percent of the positive radiative forcing from anthropogenic greenhouse gases. In this way, aerosols benefit us, because without them the net radiative forcing would be higher and global warming would be worse. But aerosols have a dark side – they are also one of the main components of air pollution around the world, which kills millions of people every year.

As poorer countries begin to clean up their environment, we expect to see the aerosol abundance in the atmosphere diminish. Although such reductions improve public health,

they also make global warming worse by reducing the cooling that aerosols provide. This is another factor that must be considered in climate change policy.

6.2.3 Total Net Forcing

Summing all of the radiative forcings discussed above, as well as some minor ones that I did not discuss, we get a net radiative forcing of $+2.5 \text{ W/m}^2$ between 1750 and 2018. This total comes from positive forcings, primarily the greenhouse gases, partially canceled by negative radiative forcing, primarily aerosol forcing. Virtually all of these radiative forcings are tied to human activities.

Let me repeat what this value means: If we made all of the changes in greenhouse gases, aerosols, and other factors that occurred over this period instantaneously and without letting the atmosphere warm, $\Delta(E_{\text{in}} - E_{\text{out}})$ would be $+2.5 \text{ W/m}^2$. This means that human activities have perturbed the Earth's energy balance in such a way that the planet is accumulating energy, leading to warming.

As the planet warms, E_{out} increases (e.g., Figure 6.2b). Measurements of the Earth's energy balance show that, for the present-day Earth, E_{in} exceeds E_{out} by 0.8 W/m^2 . This means that the planet has warmed up enough in the past 250 years to erase $+1.7 \text{ W/m}^2$ of the radiative forcing. The planet needs to continue warming in order to erase the remaining radiative forcing – this is warming that we are already committed to and can do little to stop.

You should now be able to see the foundation of the policies we might undertake to stabilize our climate. The temperature of the climate is on an upward trajectory because we are increasing the net radiative forcing through emissions of greenhouse gases. If we stabilize net radiative forcing, then the climate will stabilize. There are two obvious ways to do this. First, we can stop activities that produce positive radiative forcing – this basically means ceasing emissions of greenhouse gases to the atmosphere. In the policy world, this is known as mitigation. Alternatively, we could intentionally engage in activities that produce stronger negative radiative forcing – for example, we could add aerosols to the atmosphere – thereby canceling out the increasingly positive radiative forcing from continued greenhouse-gas emissions. This latter approach is what is commonly referred to as solar-radiation management geoengineering. I will have more to say about these approaches in Chapter 11.

6.3 Climate Sensitivity

6.3.1 No-feedback Calculation

The previous section described the first half of the climate problem: how humans have perturbed the planet's energy balance. In this section, we answer the second half of the climate problem: how much the climate must warm to re-establish energy balance.

Let's begin with a simple calculation. Let's assume an Earth-like planet with no atmosphere. E_{in} for this planet is 238 W/m^2 , and the surface temperature is 254.55 K (in previous sections, we've rounded this to 255 K , but we need the extra digits of precision here). Now

let's imagine that the Sun gets brighter so that E_{in} increases by 1 W/m^2 . In other words, we are applying a $+1 \text{ W/m}^2$ radiative forcing to the planet.

In response, the planet will warm until energy balance is re-established, which occurs when E_{out} has increased to 239 W/m^2 . We can figure what temperature this corresponds to by solving

$$E_{\text{out}} = 239 = \sigma T^4$$

for T , which yields a new equilibrium temperature of the planet of 254.80 K . This means that the application of a $+1 \text{ W/m}^2$ radiative forcing caused this planet to warm by 0.25 K .

This value, 0.25 K of warming per W/m^2 of radiative forcing, is our first estimate of what we call *climate sensitivity*.² We can use this to figure out how much warming will result from the application of an arbitrary amount of radiative forcing. For example, if the Sun gets brighter, resulting in a radiative forcing of $+9 \text{ W/m}^2$, this planet would warm up by $9 \text{ W/m}^2 \times 0.25 \text{ K}/(\text{W/m}^2) = 2.3 \text{ K}$.

For historical reasons, climate sensitivity is most frequently expressed as the warming per doubled carbon dioxide. Earlier in the chapter, I told you that doubled carbon dioxide imposed a radiative forcing of $+4 \text{ W/m}^2$, so 0.25 K per W/m^2 could be equivalently expressed as 1.0 K per doubled carbon dioxide. When scientists talk, the “for doubled carbon dioxide” is frequently left off, and scientists often just say “the climate sensitivity of the planet is 1 K ” with everyone understanding that this is the warming for doubled carbon dioxide.

6.3.2 Fast Feedbacks

But this answer is not complete because it ignores a set of important processes that have a huge impact on the climate: *feedbacks*. Feedbacks do not initiate warming, but they amplify an initial warming. One such feedback is summarized in Figure 6.8, and it starts with an initial warming, due, for example, to a brightening Sun or addition of greenhouse gases to the atmosphere. Because ice melts reliably at 0°C , this initial warming reduces the amount of ice on the Earth's surface – and, as discussed in Subsection 2.2.3, we actually see this happening today. If the melting ice uncovers a dark surface, such as ocean, then this decreases the average planetary albedo (i.e., makes the planet less reflective), which leads to more absorption of solar radiation and additional warming. This additional warming leads to even more melting of ice, which leads to further decreases in albedo and further warming, and so on. This is known as a feedback loop.

The net effect of the feedback loop shown in Figure 6.8 is to amplify the initial warming from the addition of greenhouse gas. This amplification of the warming is referred to as a

² What we have calculated should technically be referred to as the *equilibrium climate sensitivity* because it is the warming after the system reaches equilibrium. However, the word “equilibrium” is normally dropped, so when a scientist refers to climate sensitivity, she almost always means equilibrium climate sensitivity.

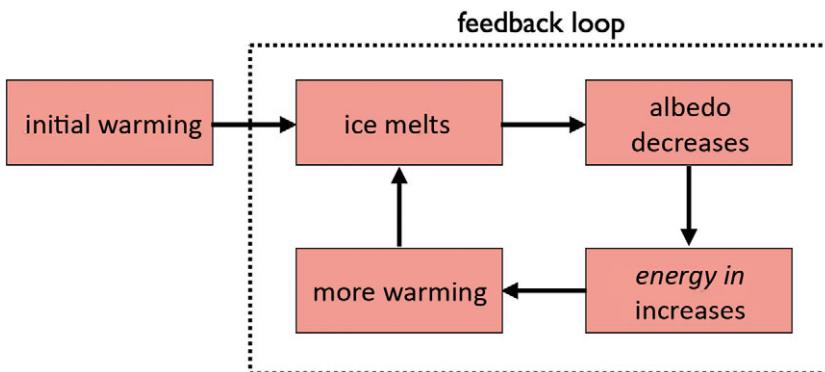


Figure 6.8 The ice-albedo feedback loop.

positive feedback. You can also have a *negative feedback*, which acts to reduce the initial warming. Imagine a planet that is covered with flowers of two colors: white and black. As the temperature of the planet goes up, the white flowers prosper while black flowers die. This means that, as a planet warms, the planet also becomes whiter – i.e., the albedo goes up. Such a process would lead to less warming than we would get if the albedo were constant. Thus, the flowers generate a negative feedback.

There are several important feedbacks in our climate system. The feedback just described, in which warmer temperatures melt ice, leading to reduced albedo and additional warming, is known as the *ice-albedo feedback*. The most important feedback in our climate system is the *water-vapor feedback*, which arises because a warmer atmosphere can hold more water vapor. Thus, global warming leads to increased atmospheric humidity, and because water vapor is itself a greenhouse gas, this leads to additional warming. Both the ice-albedo and water-vapor feedbacks are positive, meaning that they amplify an initial warming.

The biggest negative feedback is known as the *lapse-rate feedback*. Because power radiated by a blackbody is equal to σT^4 , a warmer atmosphere radiates more power to space. It turns out that the upper atmosphere warms more than the surface in a warming climate, meaning that the increase in E_{out} is larger than for a planet where the atmosphere and surface warm in unison. This enhanced warming and radiation from the upper atmosphere offsets some of the initial warming.

The biggest debate among scientists today is about *cloud feedback*. Clouds affect the climate in two opposite ways. First, they reflect sunlight back to space, reducing *energy in*, which tends to cool the climate. Second, they absorb infrared radiation emitted by the surface, decreasing *energy out* just like a greenhouse gas, and this tends to warm the climate. The net effect of clouds on the climate is therefore the difference of these two opposing effects. In our present climate, the reflection of solar radiation is slightly larger than the heat-trapping effects, so clouds reduce $E_{\text{in}} - E_{\text{out}}$ for the Earth by roughly 25 W/m^2 .

This could, however, change in the future. If, in response to an initial warming, the cooling effect of clouds is enhanced, then the effect of clouds on the planet's energy budget will become more negative, and clouds will act to reduce the initial warming and therefore be a negative feedback. In contrast, if the heat-trapping effect is enhanced, then the clouds'

radiative effect will become less negative, and clouds will amplify the initial warming and therefore be a positive feedback. Although the exact magnitude is uncertain, the scientific community is confident that the climate feedback is positive, meaning that clouds amplify warming.

Feedbacks discussed in this section are known as fast feedbacks because they occur rapidly enough in response to changes in surface temperature that they will play an important role in the evolution of climate change over the coming century. Water vapor, clouds, and the lapse rate all respond within a week or so to changes in surface temperature, and therefore their impact on *energy in* and *energy out* is nearly instantaneous. The response time of much of the ice on the planet is more seasonal, and the associated feedbacks are also categorized as fast.

6.3.3 Impact of the Fast Feedbacks

To get more quantitative about feedbacks, let us first go over some basic feedback math. For each feedback discussed in the previous section, we can express its strength as g , which is the additional fractional warming produced by one trip through this feedback loop per degree of initial warming. Thus, in response to an initial warming ΔT_i , the first trip through the feedback loop produces additional warming of $g\Delta T_i$. But the feedback operates on this additional warming, and this produces additional warming of $g(g\Delta T_i) = g^2\Delta T_i$. The feedback then operates on this additional warming too, leading to an additional warming of $g^3\Delta T_i$. This goes on forever, so the final warming ΔT_f after this feedback amplifies the initial warming is

$$\Delta T_f = \Delta T_i + g\Delta T_i + g^2\Delta T_i + g^3\Delta T_i + g^4\Delta T_i + \dots \quad (6.2)$$

We can write this more compactly as

$$\Delta T_f = \sum_{k=0}^{\infty} g^k \Delta T_i \quad (6.3)$$

The math ninjas among you will recognize that this infinite series can be rewritten more simply as

$$\Delta T_f = \frac{\Delta T_i}{(1-g)} \quad (6.4)$$

If $g = 0$, then there is no feedback, and the final temperature change is equal to the initial temperature change. If g is between 0 and 1, then ΔT_f is larger than ΔT_i , meaning the feedback is positive. If g is less than 0, then ΔT_f is less than ΔT_i , meaning the feedback is negative.

As positive feedbacks get stronger and g approaches 1, the denominator in Equation 6.4 approaches 0 and ΔT_f approaches infinity. This should make sense from visual inspection of Equation 6.2: If $g = 1$, then each subsequent term is as big as the previous one and, because

the series is infinite, the sum must also be infinite. In this situation, strong positive feedbacks generate what is referred to as a “runaway greenhouse effect” where an initial temperature perturbation leads to a very, very large temperature rise.

With multiple feedbacks operating, the g term in Equations 6.2–6.4 is the sum of the feedback values from the individual feedbacks:

$$g = g_{\text{ia}} + g_{\text{wv}} + g_{\text{cloud}} + g_{\text{lr}} \quad (6.5)$$

where g_{ia} is the ice-albedo feedback, g_{wv} is the water-vapor feedback, g_{cloud} is the cloud feedback, and g_{lr} is the lapse-rate feedback.

The strongest feedback is the water-vapor feedback, with a magnitude $g_{\text{wv}} \approx 0.6$. This feedback is big enough that, by itself, it would more than double the initial warming ΔT_i . The ice-albedo feedback is substantially weaker, with a magnitude $g_{\text{ia}} \approx 0.15$. Because it is a negative feedback, the lapse-rate feedback has a negative magnitude $g_{\text{lr}} \approx -0.25$. Finally, the cloud feedback is quite uncertain, but most scientists would put its magnitude at $g_{\text{cloud}} \approx 0\text{--}0.25$.

Summing these individual feedbacks, we get a total feedback parameter for our climate of $g = 0.5\text{--}0.75$. Plugging this into Equation 6.4, we find that $\Delta T_f = 2\text{--}4 \Delta T_i$. Thus, half to three-quarters of the warming we experience comes from feedbacks rather than the direct heating from greenhouse gases. This is why feedbacks occupy much of the scientific debate over climate change.

In Subsection 6.3.1, I calculated the no-feedback climate sensitivity for our mythical no-atmosphere Earth to be 1 K for doubled carbon dioxide. This turns out to be a surprisingly good estimate for the Earth – estimates using detailed computer simulations of the Earth predict a warming of about 1.2 K in response to doubled carbon dioxide but before any amplifications by feedbacks.

Using $\Delta T_i = 1.2$ K, the warming after feedbacks have amplified it will be $\Delta T_f = 2.4\text{--}4.8$ K. More sophisticated analyses conclude that the climate sensitivity is likely in the range 2.5 K to 4.0 K, with a best estimate of 3 K.

Given that doubled carbon dioxide corresponds to a radiative forcing of $+4 \text{ W/m}^2$, we can also express the sensitivity as the warming per unit of radiative forcing. The climate sensitivity in these units is $0.63\text{--}1.0 \text{ K/(W/m}^2)$, with a best estimate of $0.75 \text{ K/(W/m}^2)$. Knowing the climate sensitivity in these units is very useful. For example, in Section 6.2 we calculated that the radiative forcing for a 5 percent increase in solar constant is $+12 \text{ W/m}^2$. We can now calculate how much warming that would produce by multiplying this radiative forcing by the climate sensitivity of $0.75 \text{ K/(W/m}^2)$, yielding a warming of 9 K.

6.4 Slow Feedbacks

In contrast to fast feedbacks, *slow feedbacks* include processes that respond slowly to increasing surface temperature, so they require long periods of warmth before they significantly alter *energy in* or *energy out*. For example, the Greenland and Antarctic ice sheets are so big that

they will take millennia to completely respond to a change in temperature. The ice-albedo feedback associated with ice sheets would therefore be categorized as a slow feedback. These slow feedbacks will cause additional warming beyond that predicted by the fast feedbacks.

Another slow feedback revolves around the fact that there are large amounts of carbon stored in the ground. One of these carbon reservoirs is permafrost, which was discussed in Subsection 5.2.1. This permafrost contains dead organic plant matter that is kept intact as long as the ground remains frozen. If a warming climate leads to the thawing of permafrost, then the organic matter in it thaws out and decays, releasing the carbon back into the atmosphere in the form of either carbon dioxide or methane.

We know that permafrost is indeed thawing, which is consistent with the large warming in the Arctic over the past few decades (e.g., see Figure 2.3b). In Alaska, for example, roads and buildings constructed on permafrost under the assumption that it would never thaw are now suffering damage as the permafrost thaws and the ground underneath begins shifting. In Siberia, thawing permafrost formed during the last ice age is revealing frozen oddities such as intact woolly mammoths that died 20,000 years ago.

This opens the possibility of a *carbon-cycle feedback*, in which an initial warming leads to the release of large amounts of carbon dioxide and methane that are currently frozen in the ground or otherwise sequestered. The release of these greenhouse gases leads to more warming and the further release of greenhouse gases. The occurrence of such a feedback in the next few centuries is speculative, but there is reasonably strong evidence that they have occurred in the past, such as during ice-age cycles. I will return to this point when I discuss ice ages in Chapter 7.

Another slow feedback involves vegetation. It has long been known that the distribution of vegetation on the Earth's surface is governed to a large extent by the climate, through the distribution of precipitation, temperature, sunlight, and other such factors. Recently, however, it has been realized that changes in vegetation can also affect the climate. For example, the conversion of a forest to grassland will increase the albedo (because the forest is darker than the grassland), thereby tending to cool the climate. Changes in vegetation can also directly impact exchanges of heat, water, and momentum between the surface and atmosphere, or modify the rate of uptake of carbon dioxide by the vegetation. This introduces the possibility of vegetation feedbacks in which changes in climate lead to changes in vegetation, which in turn lead to additional changes in climate.

Probably the slowest feedback is the weathering thermostat, which I talked about in Section 5.3. As the Earth's surface warms, the total amount of rainfall will also increase. The increase in rainfall in turn increases the rate of chemical weathering, which removes carbon dioxide from the atmosphere. The reduction in atmospheric carbon dioxide acts to offset some of the initial warming, so this is a negative feedback that tends to stabilize the Earth's temperature. That is certainly good news, but the bad news is that the weathering thermostat operates on geologic time scales, so it only has an impact on the climate over millions of years. We should not expect the weathering thermostat to ameliorate warming over the next century – or over any time period that human society cares about.

In general, slow feedbacks are much more uncertain than fast feedbacks because they are so slow that modern Earth science, which is really only a few decades old, simply does not

have data extending over periods long enough to observe, understand, and quantify them. Nevertheless, most of the evidence we have is that they are net positive, meaning that they will increase warming over the coming millennia above what would be predicted with just the fast feedbacks. They also continue to compel our attention because many of the worst-case climate scenarios involve these slow feedbacks and the long-term warming they cause.

Aside 6.1: Feedback versus radiative forcing

It is worth explicitly discussing the differences between radiative forcings and feedbacks. Feedbacks are processes that are initiated by changes in the climate, so feedbacks do not cause climate change. Rather, positive feedbacks amplify and negative feedbacks ameliorate an initial warming.

Water vapor, for example, is considered a feedback because the amount of water vapor in the atmosphere is set by the surface temperature of the Earth. If the surface temperature increases, then the amount of water in the atmosphere will also increase, leading to additional warming.

Radiative forcings, in contrast, affect the climate but are themselves unaffected by the climate. The changes in carbon dioxide, methane, and the like between 1750 and 2005 are fundamentally unrelated to the Earth's temperature; instead, they are driven by economic activities of human society. Ditto for aerosols.

A confusion arises because some things can be both a radiative forcing and a feedback. For example, although carbon dioxide has been a radiative forcing over the past two centuries, it can also be a feedback if warming temperatures lead to the release of carbon dioxide. Changes in vegetation are a radiative forcing when humans are modifying the vegetation, but they are a feedback when it is the climate that causes the modification.

In most cases, it is clear whether a process is a radiative forcing or feedback. The increase in carbon dioxide over the last two centuries is clearly driven by human activities, not surface temperature, so it is certainly a radiative forcing. Other processes are more ambiguous. For example, changes in clouds are a forcing if they are altered by aerosols emitted from human activities, but a feedback if they are altered by changes in surface temperature. Scientists have done their best to separate these processes in our evaluation of the evidence, but this remains an uncertainty in our understanding.

6.5 Chapter Summary

- A radiative forcing is an energy imbalance imposed on the Earth. It is calculated as the change in *energy in* minus *energy out* after the imposition of the specific change in the climate but *before the temperature of the planet has adjusted in response*.
- In response to a radiative forcing, the Earth's temperature adjusts so that energy balance is re-established.

- Because of the Earth's thermal mass, this adjustment happens over time. There is a relatively rapid warming in the first few decades after the application of a radiative forcing as the ocean's mixed layer warms. After that, it is the warming of the deep ocean that sets the pace of warming. Given the enormous heat capacity of the deep ocean, this warming takes millennia.
- The increase in greenhouse gases since 1750 has imposed a radiative forcing of $+3.5 \text{ W/m}^2$. The increase in carbon dioxide is responsible for $+2.2 \text{ W/m}^2$, or more than half of the total forcing. The change in aerosols since 1750 has imposed a net radiative forcing of -1.1 W/m^2 . This means that aerosols offset approximately 30 percent of the radiative forcing from increasing greenhouse gases. Summing these and several other small changes, we get a net radiative forcing over this time period of $+2.5 \text{ W/m}^2$, almost entirely due to human activities.
- Positive feedbacks amplify and negative feedbacks ameliorate an initial warming. For the problem of modern climate change, we are mainly concerned with the following fast feedbacks: water vapor, ice-albedo, lapse rate, and clouds. Together, they double to quadruple an initial warming.
- Feedbacks are processes that respond to changes in the surface temperature, whereas forcings are unrelated to the surface temperature. Thus, feedbacks do not initiate climate change, but forcings do.
- The Earth's climate sensitivity, which is conventionally defined as the equilibrium temperature increase caused by a doubling of carbon dioxide, is likely 2.5–4.0 K, with a best estimate of 3 K. In terms of radiative forcing, the climate sensitivity is $0.63\text{--}1.0 \text{ K/(W/m}^2\text{)}$, with a best estimate of $0.75 \text{ K/(W/m}^2\text{)}$.
- On long time scales, slow feedbacks become important and could cause significant temperature increases beyond those predicted by the fast feedbacks. These slow feedbacks include destruction of large parts of the Greenland and Antarctic ice sheets, which will change the planet's albedo, thawing permafrost releasing carbon dioxide and methane, or large-scale changes in the distribution of vegetation.

See www.andrewdessler.com/chapter6 for additional resources for this chapter.

TERMS

- Aerosol direct effect
- Aerosol indirect effect
- Aerosols
- Carbon-cycle feedback
- Climate sensitivity
- Cloud-condensation nuclei (CCN)
- Cloud feedback
- Feedbacks (positive and negative)

Ice-albedo feedback
 Lapse-rate feedback
 Radiative forcing
 Ship tracks
 Slow feedbacks
 Water-vapor feedback

PROBLEMS

1. How much does the Earth's solar constant have to increase in order to generate a radiative forcing of $+1 \text{ W/m}^2$ for the Earth?
2. Define climate sensitivity. What is the currently accepted range and our best estimate for our climate?
3. Assume an n -layer planet with a specified E_{in} . The surface temperature for this planet can be written (by combining Equations 4.2 and 4.5):

$$T = \sqrt[4]{\frac{(n+1)E_{\text{in}}}{\sigma}} \quad (6.6)$$

- (a) One way to calculate the no-feedback climate sensitivity is to estimate the change in temperature for a $+1 \text{ W/m}^2$ increase in E_{in} . Take the derivative of Equation 6.6 to obtain the formula for dT/dE_{in} .
- (b) Plug in values for $n = 0$ and $E_{\text{in}} = 238 \text{ W/m}^2$. Do you get the same answer we got in Subsection 6.3.1?
- (c) What is the no-feedback sensitivity (in K per W/m^2) for a one-layer planet with the same E_{in} ?
4. Imagine that our Sun brightens by 1 percent instantaneously.
 - (a) How long would it take for the Earth to reach its new equilibrium temperature? Is this longer or shorter than the time it would take Mars or Mercury to reach their respective equilibrium temperatures?
 - (b) What radiative forcing does this change correspond to?
 - (c) Approximately how much warming would this brightening eventually cause?
 - (d) How would the calculated radiative forcing change if the brightening takes place over 1,000 years instead of instantaneously?
5. Explain why changes in ice, which modify albedo and therefore affect planetary energy balance, are considered a feedback and not a forcing.
6. The albedo changes from 0.3 to 0.31 on the Earth. What is the radiative forcing associated with this change?
7. When considering how long it takes for radiative forcing to warm up the planet, it is useful to think about the heat capacity of the climate system, which tells us how many joules are required to raise the temperature by 1 K.

The heat capacity of the climate system comes mainly from the ocean, and we can estimate it to be 6×10^{24} J/K (this means that, if you add 6×10^{24} J to the Earth system, the climate will warm by 1 K).

- (a) Imagine you impose a radiative forcing of $+2.3 \text{ W/m}^2$, what rate of warming will result? Express your answer in $^{\circ}\text{C/century}$.
- (b) How does this compare with the actual rate of warming of the Earth? (This was discussed in Chapter 2.)
- 8. Imagine a planet where $S = 1,360 \text{ W/m}^2$ and $\alpha = 0.3$.
 - (a) If $n = 0$, what is the temperature of this planet?
 - (b) If S increases to $1,370 \text{ W/m}^2$ and n remains equal to 0, what is the new temperature?
 - (c) Let us include a water-vapor feedback: S increases to $1,370 \text{ W/m}^2$, but the number of layers, n , is a function of surface T : $n(T) = (T - 254.5)/100$. What is the new surface temperature?
 - (d) Using the answers to b and c and assuming that no other feedbacks are operating, what is the value of g for this climate?
- 9. How much of a change in albedo is required to completely cancel a doubling of carbon dioxide on the Earth (put another way, how much of a change in albedo is required to generate a radiative forcing of -4 W/m^2)?
- 10. Imagine that, in addition to the fast feedbacks discussed herein, there was also a fast negative “flower” feedback like that described in this chapter (as the planet warms, white flowers prosper while black ones die out), and that it had a magnitude $g = -0.3$. Estimate the Earth’s climate sensitivity.
- 11. Assume that the Earth has warmed by 5 K since the last ice age, and the change in radiative forcing over that time was $+6.7 \text{ W/m}^2$. On this basis, calculate the climate sensitivity.
 - (a) Express the climate sensitivity in K per W/m^2 .
 - (b) Express the climate sensitivity in K per doubled CO_2 .
- 12. In the northern hemisphere, E_{in} maximizes on June 21, when the Sun is most directly overhead. You might therefore expect temperatures to be highest on that day. But for the US Gulf Coast, temperatures do not reach their hottest until mid-August – several months after the maximum in E_{in} . Why?
- 13. Imagine a planet with a solar constant of $1,500 \text{ W/m}^2$ and an albedo of 0.6. Which would cause that planet’s climate to warm more, a 1 percent increase in solar constant or a 0.01 decrease in albedo?
- 14. Imagine a planet with a solar constant of $3,500 \text{ W/m}^2$ and an albedo of 0.8. The planet has no atmosphere.
 - (a) What is the planet’s climate sensitivity in K per W/m^2 ?
 - (b) If the Sun gets 10 percent dimmer, how does the temperature change?
- 15. Aerosols have a short lifetime, so once we stop emitting them, their atmospheric abundance will go to zero in a few months. This is a very important goal – aerosols are one of the primary components of air pollution, which kills millions of people

around the world every year. However, these aerosols are also cooling the climate, so cleaning up the air and saving these lives will remove something that's masking about one-third of the radiative forcing from greenhouse gases. Estimate how much warming we will eventually experience if we clean up the air and aerosol radiative forcing goes to zero (assume all other sources of radiative forcing are unchanged).

7

Why Is the Climate Changing?

In Chapter 2, we detailed the overwhelming evidence that the Earth’s climate is changing – evidence so overwhelming that the IPCC describes the warming as “unequivocal.” At this point, the most heated argument is over the cause of the warming: Is it caused by human activity, or is it natural? In this chapter, we address this question.

7.1 Context of the Recent Warming

Back in Chapter 2, you saw that the climate has varied widely over the Earth’s 4.5-billion-year history – from an ice-covered snowball Earth hundreds of millions of years ago to the Eocene, 50 million years ago, a period so warm that there was no permanent ice anywhere on the planet. Humans obviously played no role in these changes.

Thus, it’s clear that natural mechanisms exist that are capable of driving large changes in the climate. On the other hand, we saw in Chapter 5 that humans have dumped hundreds of billions of tonnes of carbon dioxide into the atmosphere since the industrial revolution, and based on what we learned in Chapter 4, we expect this to warm the climate. It is therefore completely reasonable to ask whether natural mechanisms, human activities, or some combination are responsible for the warming of the last two centuries.

Our strategy to answer this is to examine all of the mechanisms that we know can change the climate and assess the evidence supporting each one as the cause of the modern warming – a climate whodunit, if you will. We will then reject those mechanisms with an alibi and identify the one that looks guiltiest.

You will see that a careful assessment of all of the possible causes yields the quite certain conclusion that greenhouse gases released by human activities are guilty beyond a reasonable doubt for the recent warming.

7.2 The First Suspect: Plate Tectonics

As you probably know, the Earth’s continents are moving. Not fast, mind you – they move at about the rate that your fingernails grow – but over tens of millions of years, this *plate tectonics* can substantially alter the arrangement of the continents across the Earth’s surface. Such changes can lead to large changes in the climate through several mechanisms.

For example, the location of continents determines whether ice sheets form. The most important requirement for growth of an ice sheet is summer temperatures cool enough

that snow falling during the winter does not melt during the following summer. This is most favorable for land at high latitudes, which get the least sunlight. Ice sheets matter to the climate because they reflect sunlight, so the formation of an ice sheet increases planetary albedo, thereby increasing the reflection of solar radiation back to space and cooling the planet.

In addition, the location of the continents determines the ocean circulation. The oceans carry prodigious amounts of heat from the tropics to the polar regions, so changing the ocean circulation can alter the relative temperatures of the tropics and polar regions. A good example of this happened 30 million years ago when the Antarctic Peninsula separated from the southern tip of South America, opening the Drake Passage. This isolated Antarctica and allowed winds and water to flow unhindered around it. This intense circumpolar flow reduced the transport of warm water and air from the tropics to the South Polar region, cooling the Antarctic and helping build the Antarctic ice sheet.

Plate tectonics can also indirectly affect the climate by regulating atmospheric carbon dioxide. As I discussed in Chapter 5, carbon dioxide is slowly removed from the atmosphere by chemical weathering, which occurs when atmospheric carbon dioxide dissolves in rainwater and then reacts with sedimentary rocks. The movement of the continents can change the pattern of rainfall and expose new rock to the atmosphere, changing the locations and rate of chemical weathering – thereby altering the amount of carbon dioxide in the atmosphere.

For example, 40 million years ago the Indian subcontinent collided with Asia, forming the Himalayas and the adjacent Tibetan Plateau. This change in surface topology led to changing wind patterns, bringing heavy rainfall onto a vast expanse of newly exposed rock. The resultant chemical weathering drew down atmospheric carbon dioxide over a period of tens of millions of years. This is one of the reasons the planet cooled over the past 40 million years (as shown in Figure 2.11).

Thus, plate tectonics can indeed affect the climate. But could it be responsible for the rapid warming of the past few decades? The answer is no because the movement is too slow – it takes millions of years for continental movement to cause significant climate change. Continental movements simply cannot significantly modify the climate over a few decades.

7.3 The Sun

As we saw in Chapter 4, one of the factors that controls our climate is the solar constant S . So if the Sun brightens or dims, we expect the climate to respond by warming or cooling. It is therefore reasonable to ask whether the recent warming of the climate can be explained by an increase in the brightness of the Sun.

It is well known that the Sun's output varies on many time scales. For example, solar physicists believe that, over the Sun's 5-billion-year life, as the Sun burned hydrogen and produced helium, the rate of fusion in the Sun has increased as the buildup of helium increased in the density of the Sun's core. This has caused the Sun to become about 30 percent brighter over this time.

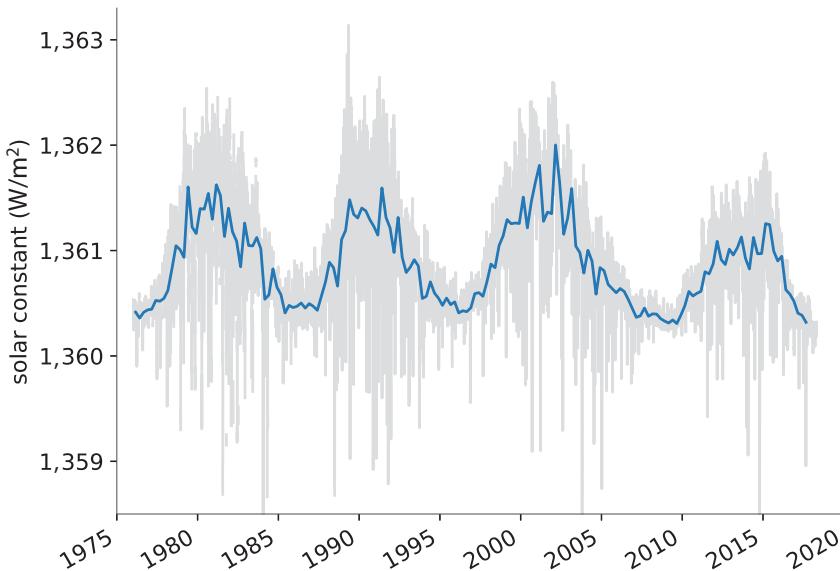


Figure 7.1 Satellite measurements of the solar constant over the last few decades. Seasonal changes in the Earth–Sun distance have been removed. Data are from PMOD/WRC, Davos, Switzerland, version 42_65_1805, including data from the VIRGO Experiment on the cooperative ESA/NASA Mission SoHO (<ftp://ftp.pmodwrc.ch/pub/data/irradiance/composite/DataPlots/>, accessed May 2, 2020).

Since the late 1970s, instruments on satellites have been accurately measuring the solar constant; the measurements are plotted in Figure 7.1. Over this period, there is a clear 11-year cycle, during which the solar constant varies by about 0.1 percent (about 1 W/m^2). The climate system does not respond to such high-frequency variations, however. In order for the Sun to be responsible for the recent warming, there would need to be a sustained, long-term increase in the solar constant over the past few decades. The measurements show no evidence of this.

The Sun’s influence on climate prior to the 1970s is more difficult to determine because there were no satellite measurements of the solar constant. 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 output of the Sun has changed little over the past few hundred years.

Thus, we find that observations of the Sun rule out a significant role of changes in the solar brightness as an explanation of modern climate change.

7.4 The Earth’s Orbit

The solar constant is determined not just 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 constant would increase even if the brightness of the Sun did not change.

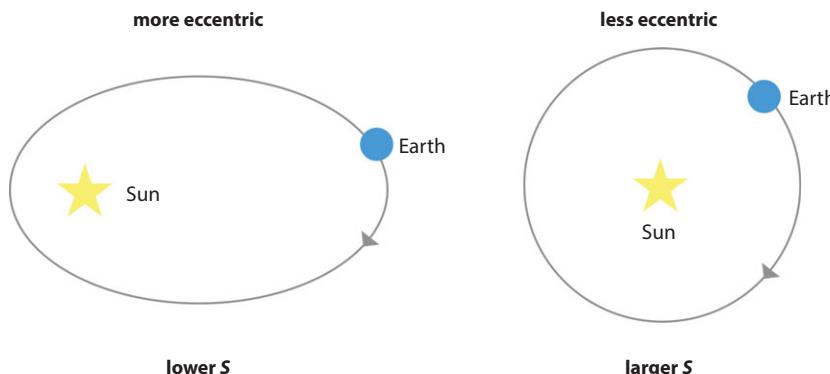


Figure 7.2 Schematic illustrating how the eccentricity of the Earth's orbit (how elliptical it is) varies with a period of 100,000 years or so.

This is relevant because the Earth's orbit is not a perfect circle: It is an ellipse whose *eccentricity* – the ratio of the length of the ellipse to the width – varies with time. Over the course of 100,000 years or so, the orbit cycles between an orbit that is more eccentric (more elliptical) and one that is less eccentric (more circular) (Figure 7.2).¹ As the orbit becomes more elliptical, the average Earth–Sun distance increases, and the average amount of solar energy falling on the Earth decreases. For the Earth's orbit, this causes the annual average solar constant to vary by approximately 0.5 W/m^2 over the 100,000-year cycle.

Other aspects of the Earth's orbit can also vary, such as the timing of the closest approach of the Earth to the Sun. Today, the Earth is closest to the Sun during January, when it is wintertime in the northern hemisphere (Figure 7.3). Over time, the date of closest approach will move through the calendar, reaching July in 11,500 years. Over the following 11,500 years, it will complete the cycle.

Another important variation is the tilt of the Earth (also known as the *obliquity*). Today, the Earth's spin axis is tilted 23.5° from vertical (Figure 7.4). However, over the next 41,000 years, the Earth's tilt will complete a cycle through a range of tilt angles from 22.3° to 24.5° .

Changing the date of closest approach to the Sun or the tilt of the Earth does not change the Earth–Sun distance, so it does not change the solar constant. Rather, these variations change how sunlight is distributed over the planet, in both latitude and season. For example, increasing the tilt of the planet increases the amount of sunlight hitting the polar regions and decreases the amount hitting the tropics. Because the polar regions tend to be covered by ice, more sunlight falling on the poles means more sunlight reflected back to space. Thus, increasing the tilt of the planet can alter the climate.

We see in the paleoclimate record nearly perfect agreement between the ice-age cycles (Figure 2.13) and the variations in the Earth's orbit. As I discussed earlier in this chapter, the growth of big, continental-scale ice sheets, such as existed during the last ice age, is

¹ When we specify the length of a cycle (e.g., the 100,000-year eccentricity cycle), this is the length for the eccentricity to execute one complete cycle. This means that it takes 50,000 years for the eccentricity to vary from its maximum value to its minimum, and another 50,000 years to return to its starting value.

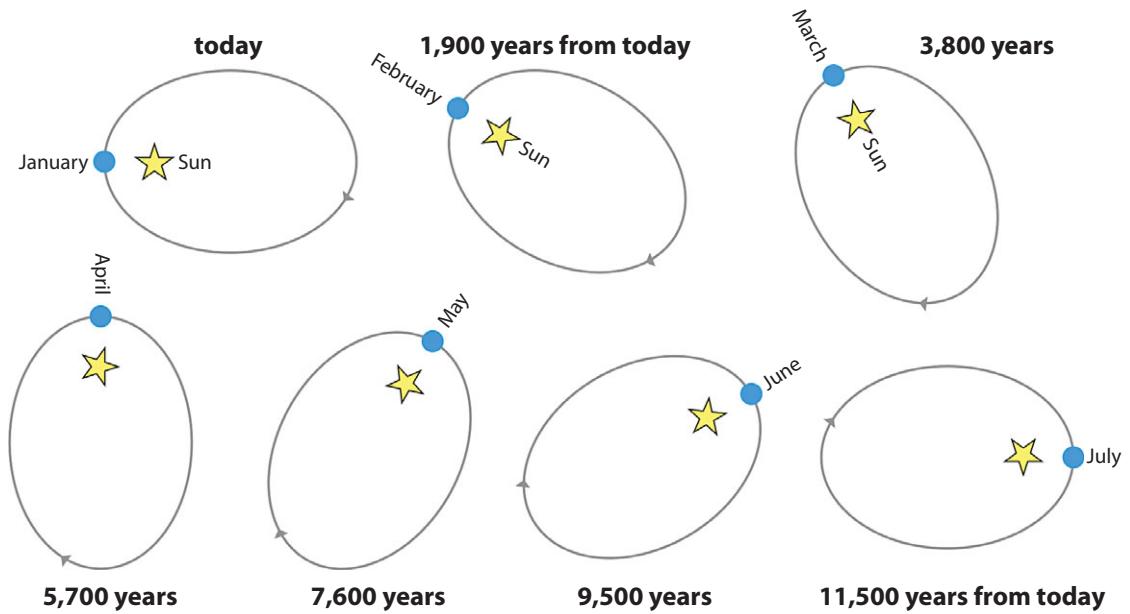
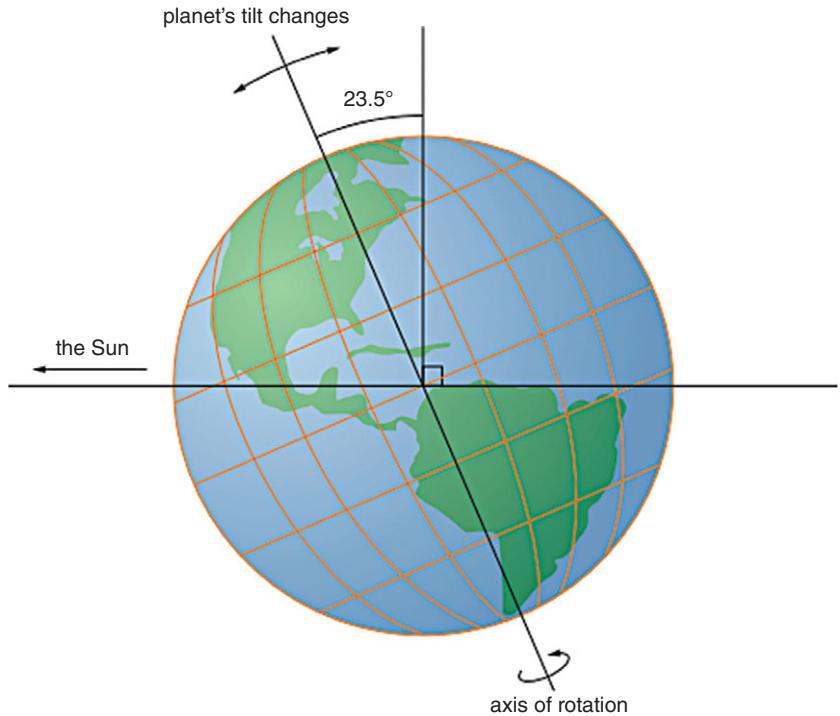


Figure 7.3 Schematic illustrating how the date of closest approach of the Earth to the Sun varies from January to July over 11,500 years.

Figure 7.4 Schematic illustrating the obliquity of the Earth (the tilt of the spin axis away from perpendicular to the orbital plane), which varies with a period of 41,000 years.



determined by high-latitude summertime temperatures – because this determines whether snow that falls during the winter survives the subsequent summer. Orbital variations regulate how sunlight is distributed over the planet and over the seasons, so they play a key role in regulating these temperatures. These orbital variations and the climate effects that follow are often referred to as *Milankovitch cycles*, after Serbian mathematician Milutin Milankovitch, who was the first one to recognize that the ice-age cycles corresponded to variations in the Earth's orbit.

But while these orbital variations are critical in ice ages, are they responsible for the warming of the past few decades? They are almost certainly not. These orbital variations are so slow that it takes thousands or tens of thousands of years to make any significant change in the amount or distribution of incoming sunlight. The warming of the past century has been much too fast to be caused by these slow orbital variations. The warming must be due to other causes.

7.5 Unforced Variability

Climate change due to changes in the output of the Sun or in the Earth's orbit are examples of *forced variability*: changes in the Earth's climate in response to an imposed energy imbalance, i.e., a radiative forcing. 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 as 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. These ENSO events are associated with large-scale shifts of rainfall and temperature patterns around the globe, and these have enormous consequences for humanity. Some regions see more rainfall during an El Niño, and some see less; some regions experience warmer temperatures than normal, while others are cooler. During a La Niña, regions typically experience the opposite of what they experience during an El Niño.

Figure 7.5 shows that these ENSO events have a big impact on the global climate – during El Niño events, the climate warms, while during La Niña events, the climate cools. In fact, many of the short-term variations in the temperature record can be traced back to ENSO events.

ENSO is the dominant and best-known source of unforced variability in the climate system. However, other modes of variability, with names like the Pacific Decadal Oscillation (PDO), are known to exist, although they are less well understood. So the relevant question is this: Could the warming of the past few decades be due to unforced variability?

There are three reasons why it's unlikely.

1. **There is no theory.** All modes of unforced variability must be traceable back to physical processes. ENSO, for example, arises from a well-studied interaction

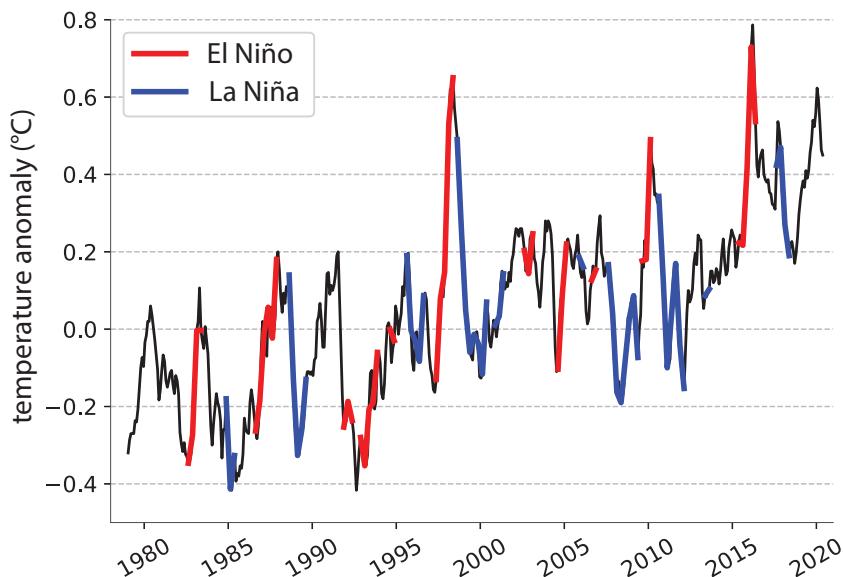


Figure 7.5 Satellite measurements of the global monthly average temperature anomaly. Red segments indicate El Niño conditions, blue segments indicate La Niña conditions, and black segments indicate neutral conditions. Temperature anomalies are relative to the 1981–2010 period. Satellite temperature data obtained from the University of Alabama, Huntsville (http://vortex.nsstc.uah.edu/data/msu/v6.0/tlt/uahncdc_lt_6.0.txt). ENSO index obtained from NOAA Physical Science Laboratory (<https://psl.noaa.gov/enso/mei/>). All data accessed October 15, 2020.

between the ocean and atmosphere. However, no one has identified a physical process for unforced variability that could produce a large, long-term global warming like the one we have been experiencing since the nineteenth century, as well as all of the other things we have observed in the climate system: an increase in heat content of the ocean, cooling of the stratosphere (discussed below), amplification of warming at high latitudes, etc.

2. **Observations do not support it.** Human activities probably had minimal impact on climate before 1800, so the climate record data before 1800 should provide a good picture of recent natural climate variability and tell us whether unforced variability is large enough to cause the modern warming. As we can see in Figure 2.15, the record between 0 AD and 1800 AD shows nothing similar to the rate and magnitude of warming of the twentieth century. Thus, the paleoproxy data provide no support for unforced variability as a possible cause of the recent warming.
3. **Computer simulations of climate do not support it.** We can also gain insight into natural climate variability by using detailed computer simulations of the climate (these will be discussed in more detail in the next chapter). These computer simulations, which are also referred to as climate models, contain all of the physics we think

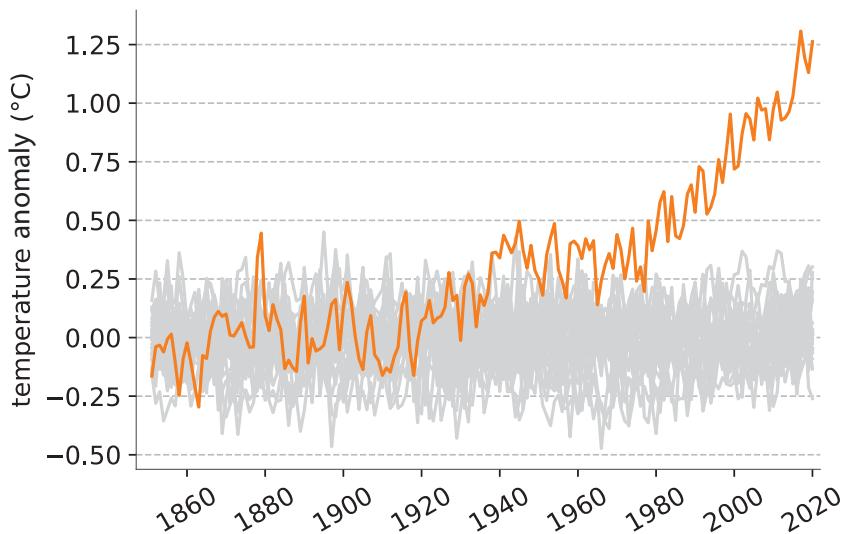


Figure 7.6 Computer simulations of the climate without any radiative forcing. The gray lines are 170-year segments from pre-industrial control runs of 26 different computer simulations. The orange line is the observed surface thermometer record (also plotted in Figure 2.2). Computer simulations are from the CMIP6 archive (<https://esgf-node.llnl.gov/search/cmip6/>), the orange line is the global average temperature anomaly from the Berkeley Earth temperature record (http://berkeleyearth.lbl.gov/auto/Global/Land_and_Ocean_summary.txt).

is going on in the climate system, and they have a good track record of simulating the climate system.

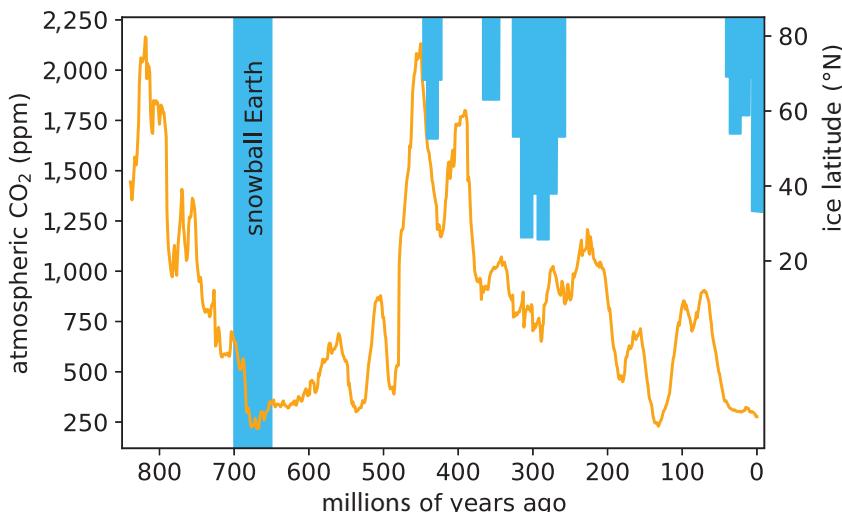
One use of these computer simulations is to perform “what if” scenarios in order to see what the climate would look like in worlds that do not exist. For example, we can run the models with no radiative forcing, in which case all temperature variations are due to unforced variability. Such simulations, shown in Figure 7.6, exhibit variations in temperature that are similar to unforced variability seen prior to 1800 in Figure 2.15, but they produce nothing resembling the rapid warming since 1900.

Ultimately, we cannot definitively exclude unforced variability in the same way we can definitively exclude, say, a brightening Sun. However, there is little evidence to support this explanation, either. So unforced variability is like a suspect in a criminal investigation who has no alibi but for whom there is also no evidence linking him to the crime. You would be hard-pressed to convict him based only on a lack of an alibi.

7.6 Greenhouse Gases

The last potential explanation for the recent warming is the increase in greenhouse gases in our atmosphere. As I’ll argue here, there is a mountain of evidence that the warming of the

Figure 7.7 Atmospheric carbon dioxide over the past 900 million years (orange line). The blue bars indicate the latitudinal extent of continental ice deposits. The snowball Earth bar indicates global or near-global ice coverage. Based on Figure 1 of Foster et al. (2017).



last two centuries is almost certainly dominated by the increase in greenhouse gases. This is based on a number of separate threads of evidence.

1. We have a robust theory. Chapter 4 provided the physical basis for why an increase in greenhouse gases would be expected to warm the planet, and Chapter 5 showed that greenhouse gases are indeed increasing, almost entirely due to human activities. Based on this, world-famous scientist Svante Arrhenius predicted – in 1896! – that our climate would undergo a long-term warming due to emissions of carbon dioxide from fossil fuel combustion.

2. The geologic record supports the theory. We talked in Chapter 2 about how the Earth fluctuated between periods of large-scale glaciation (icehouse periods) and periods with little permanent ice on the planet (greenhouse periods).² Estimates of atmospheric carbon dioxide in our atmosphere (Figure 7.7) show that icehouse conditions occur when atmospheric carbon dioxide is lower than average.³ Since ice extent is a proxy for temperature, these data allow us to conclude that variations in carbon dioxide and temperature have generally been associated with each other for much of the Earth’s history.

² Once again, do not confuse the icehouse–greenhouse cycles with ice-age cycles. Icehouse–greenhouse cycles last tens of millions of years, while ice age cycles last 100,000 years. See Section 2.3.2 to review this material.

³ Over this same time, the Sun brightened by several percent. Thus, the climate associated with a certain level of carbon dioxide a few hundred million years ago would be much cooler than the climate would be for the same amount of carbon dioxide today. This explains why widespread glaciations were occurring hundreds of millions of years ago with carbon dioxide abundances much higher than today’s.

Aside 7.1: How does science deal with outliers?

Figure 7.7 also provides a good example of why climate science is hard. Although most glaciations are associated with low carbon dioxide, the eagle-eyed among you will notice that approximately 450 million years ago there was a glaciation when carbon dioxide levels were greater than 1,500 ppm. Such a point is known as an *outlier* – a point that does not agree with the rest of the data. So-called climate skeptics might take this single point and argue that it disproves the connection between climate change and greenhouse gases. Is that a reasonable conclusion? What would a scientist think about this outlier?

There are several possible explanations for the outlier. First, the theory connecting carbon dioxide with climate may indeed be wrong, as the skeptic suggests. Second, the data may be wrong – perhaps there was no glaciation, or maybe carbon dioxide was really much lower than suggested by the proxy data. After all, we are trying to infer the conditions on the planet nearly half a billion years ago, and there are lots of ways that the proxy data could mislead us. Finally, both the data and greenhouse-gas theory could be right: there may have been something else offsetting the warming from carbon dioxide. For example, massive volcanism could have injected enough aerosols into the atmosphere to lead to low temperatures despite high abundances of carbon dioxide.

In his seminal work, *The Structure of Scientific Revolutions*, Thomas Kuhn described how incorrect scientific paradigms accumulate anomalies – places where the observations do not match theory. These anomalies accumulate until there are so many that the paradigm is simply no longer tenable, and a scientific revolution overthrows the old paradigm and replaces it with a new one.

For example, at the beginning of the twentieth century, physics was in trouble. Classical physics could not explain several well-validated observations, including the T^4 dependence of blackbody radiation (discussed in Chapter 3), atomic and molecular spectra, and the photoelectric effect. Eventually, it became apparent that classical physics simply did not work at the atomic level, and a scientific revolution occurred. What emerged was a new paradigm, known as quantum mechanics, which ruled small, atomic domains, while classical physics ruled our macroscopic, everyday world.

It is important to recognize that outliers occur in all fields, not just climate science. For example, you can find – contrary to expectations – people who smoke four packs of cigarettes each day yet who live to be 90 years old. Such anomalies frequently allow scientists to refine and extend their theories: Given that smoking causes cancer, why are some people less susceptible than others? Is it just luck, or is there a physiological basis? Importantly, though, the existence of some smoking anomalies does not cause scientists to reject the underlying idea that smoking is bad for your health.

The question that each scientist must ask individually, and the scientific community must ask collectively, is whether a particular paradigm has accumulated enough anomalies that it is no longer tenable. At present, there are not enough anomalies like the glaciation 450 million years ago to reject the dominant paradigm that greenhouse gases play a major role in determining our climate. But scientists are always looking for new anomalies – and if enough of them accumulate, eventually this theory of climate will be replaced by another one.

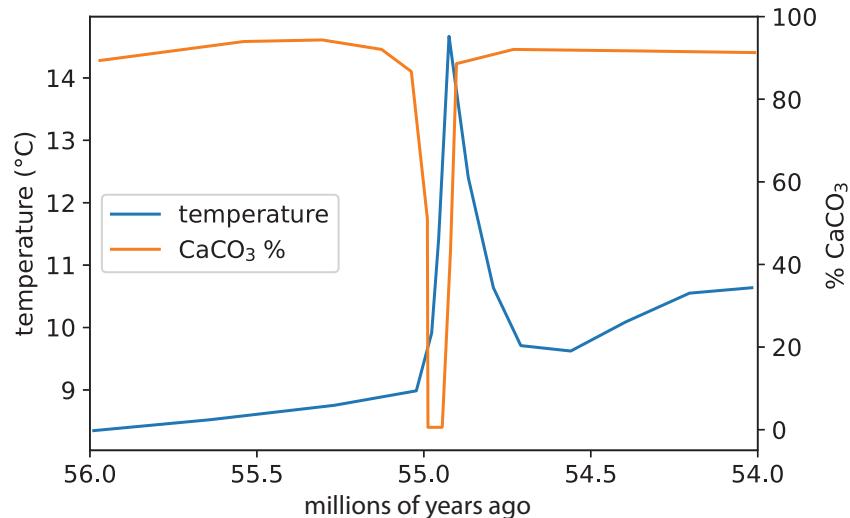
Aside 7.1: (cont.)

From a practical standpoint, though, no one expects that to occur. The paradigm that carbon dioxide exerts a strong influence on climate is based on simple, fundamental physics, and it has successfully predicted so many aspects of our climate that it is quite unlikely that the theory will turn out to be substantially wrong. This is akin to our views on smoking and lung cancer. Although it is possible that future research may disprove the link, it is a very unlikely eventuality.

More evidence of the connection between greenhouse gases and climate is the event 55 million years ago known as the Paleocene–Eocene Thermal Maximum or PETM. This event began with a massive release of either carbon dioxide or methane, which in turn led to an increase in the Earth's global average temperature of $\sim 5^{\circ}\text{C}$ over the following few thousand years (blue line in Figure 7.8). The mass of carbon was so immense that when it dissolved into the oceans, the oceans became significantly more acidic (as I discussed in Chapter 5, carbon dioxide forms carbonic acid after it dissolves in water). This in turn dissolved calcium carbonate (the material that makes up shells) in the sediments at the bottom of the ocean (orange line in Figure 7.8).

The PETM temperatures remained elevated for 100,000 years or so, which is about the length of time it takes the carbon cycle to fully remove the carbon from the atmosphere. Interestingly, the mass of carbon released, a few thousand gigatonnes, is comparable with the amount contained in all of the Earth's fossil fuels. Thus, the PETM is frequently viewed as a good analog to what will happen if humans burn all of the fossil fuels over the next few centuries.

Figure 7.8 Temperature during the Paleocene–Eocene Thermal Maximum (blue line, left-hand axis) and calcium carbonate content of ocean sediments (orange line, right-hand axis) over time (adapted from Figure 6.2 of Jansen et al., 2007).



The association between carbon dioxide and temperature is even clearer over the past few hundred thousand years. Figure 2.13 shows how carbon dioxide and temperature varied in lock step as the Earth cycled between ice ages and warm interglacials. The association between temperature and carbon dioxide, however, is a bit more complicated than the plot may at first suggest. There is strong evidence that ice-age cycles are initiated by small variations in the Earth's orbit (as discussed in Section 7.4). However, the changes in sunlight falling on the Earth in response to these slight orbital changes are too small to explain the wide temperature swings during ice-age cycles. Something must be helping the orbital variations produce the observed variations.

What is missing is carbon dioxide. It appears that small changes in climate from orbital variations lead to changes in ocean circulation, which in turn changes the uptake of carbon dioxide by the ocean. Given the large fluxes of carbon into the ocean discussed in Chapter 5, small changes in this flux can lead to large changes in atmospheric carbon dioxide. These changes in carbon dioxide amplify the initial climate perturbation. In other words, the orbital variations are the forcing, and carbon dioxide is acting here as a positive (amplifying) feedback.

Aside 7.2: A skeptical argument

During the ice ages, carbon dioxide began rising after the temperature. This proves that carbon dioxide responds to temperature, and not the other way around. Ergo, carbon dioxide cannot be causing the present-day warming. – Someone who's never read this book

As with most skeptical arguments, this one begins with a grain of truth. If you look at Figure 2.13, you can see that changes in carbon dioxide come *after* the changes in temperature. What's incorrect is what this means: It does *not* mean carbon dioxide is not an important regulator of our climate system.

The problem with this argument is that it misunderstands the difference between a climate forcing and a feedback. When you have a forcing, such as the Sun getting brighter or the addition of greenhouse gases to the atmosphere, the forcing occurs first and the temperature change occurs thereafter.

A feedback, however, is more complicated. There is an initial temperature change, followed by the feedback mechanism, followed by additional warming. For the ice-albedo feedback shown in Figure 6.8, for example, there is an initial warming, followed by a loss of ice, followed by increased absorption of solar energy, followed by more warming. It is therefore wrong to conclude that, because the temperature change occurs first, the melting ice has no effect on the climate. It does.

During the ice-age cycles, carbon dioxide acted as a feedback – a warming planet led to the release of carbon dioxide, which then caused additional warming. In that case, the warming comes first, then the increase in carbon dioxide. Thus, the lag does not mean that carbon dioxide is not affecting our climate today. In modern times, carbon dioxide is a climate forcing – humans are adding it to the atmosphere, and that is causing warming – so the increase in carbon dioxide is today occurring before the warming.

3. Computer simulations of climate provide support. More support for the link between greenhouse gases and climate comes from computer simulations of the climate. Computer simulations of the twentieth century that exclude the observed increase in greenhouse gases fail to simulate the increase in temperature over the second half of the twentieth century. This can be seen in Figure 7.9. The simulations in Figure 7.9a include natural forcings – primarily volcanoes – but no human impact on climate. This calculation reproduces many of

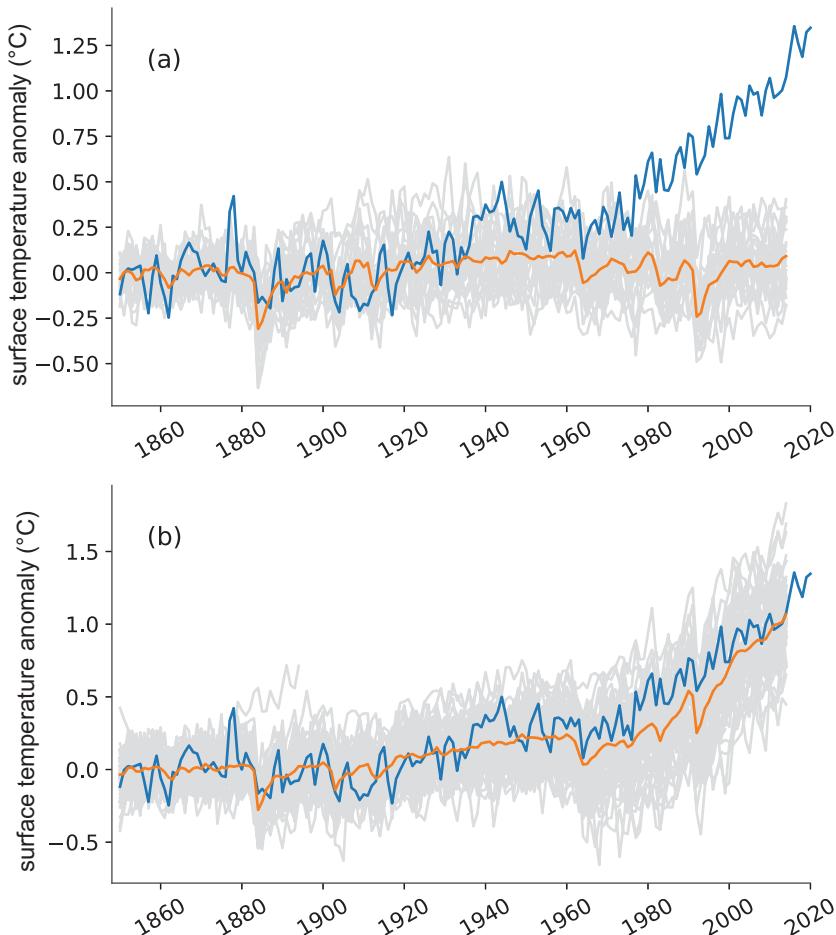


Figure 7.9 Global mean surface temperature anomalies from the surface thermometer record (blue lines) compared with simulations from climate simulations (gray lines are individual runs of different computer models, the orange line is the average of all simulations). The models include (a) only non-human natural climate forcing, mainly volcanic forcing, and (b) natural forcing and human greenhouse-gas emissions, aerosols, and ozone depletion. Anomalies are relative to the 1850–1900 mean. Climate models are from the CMIP6 archive (<https://esgf-node.llnl.gov/search/cmip6/>), surface temperature measurements are from Berkeley Earth (http://berkeleyearth.lbl.gov/auto/Global/Land_and_Ocean_summary.txt). All data accessed November 15, 2020.

the bumps and wiggles in the record, showing that these are not due to human activity. But this simulation completely fails to capture the rapid warming that began around 1960.

The simulations in Figure 7.9b include natural forcings as well as forcings from human activities – mainly greenhouse-gas emissions but also increases in aerosols and decreases in stratospheric ozone. This model captures the rapid warming since 1960 that the model with only natural forcing fails to simulate. This supports the conclusion that human greenhouse-gas emissions are responsible for the rapid late-twentieth-century warming.

4. Fingerprints of warming. Just like criminals leave unique fingerprints at the scene of a crime, different warming mechanisms have unique signatures in the pattern of warming. For example, if a brightening Sun were the cause of modern warming, we would expect the entire atmosphere to warm up. Greenhouse gases, on the other hand, leave a different fingerprint: for reasons we will not cover here, warming due to increases in greenhouse gases causes the lower atmosphere to warm, but the stratosphere to cool. Measurements from weather balloons and satellites show that the stratosphere has cooled as the lower atmosphere warms. There are many of these “fingerprints” of warming, and they provide strong support for the conclusion that the warming we are experiencing at present is due to the observed increase in greenhouse gases in our atmosphere.

7.7 Putting It Together

As we learned in Chapter 2, the Earth’s climate has varied more or less continuously for the past billion years, and probably for the entire history of the planet. Except for the climate change of the last century or so, these variations had nothing to do with human activities. Thus, when we consider the recent warming, the first thing we should do is investigate whether today’s warming is due to natural variations. We have done that and found that most natural explanations (e.g., plate tectonics, orbital variations, variations in the output of the Sun) can be decisively eliminated. Unforced variability cannot be definitively eliminated, but there is little evidence to support that it is responsible for the modern warming.

That leaves one obvious suspect. There is overwhelming evidence that the increase in greenhouse gases is the cause of the recent warming. Physics tells us that increases in greenhouse gases in our atmosphere should warm the planet, as detailed in Chapter 4. And as we saw in Chapter 5, human activities have been increasing greenhouse gases in our atmosphere. There is also observational evidence that carbon dioxide has played a key role in our climate over the past billion years. Computer simulations of the climate system cannot reproduce the observed warming without including the warming from increasing greenhouse gases. Finally, the fingerprints of warming match what we theoretically would expect from warming caused by greenhouse gases.

Taken together with the lack of a competing hypothesis, the totality of evidence that carbon dioxide is the main cause of the recent warming makes a compelling case that clearly

exceeds the threshold used in US criminal court cases of “beyond a reasonable doubt.” If you were on a jury, you should have no qualms about convicting carbon dioxide of warming the climate.

Reflecting this, there are three different conclusions we can reach, each with different levels of confidence. First:

Due to these multiple independent lines of evidence, human influence on the climate system since the mid-20th century is now an established fact.

Thus, the scientific community is 100 percent certain that humans are currently influencing the climate. Note that this statement applies only to warming since the middle of the last century, because it is only after that time that observations of the Earth system are sufficiently numerous and reliable to be able to reach this conclusion. That does not mean that humans had no influence on the climate before then – in fact, it is almost certain that we did – but rather it reflects the fact that we do not have good enough observations prior to the mid-twentieth century to prove it with enough confidence to call it a “fact.”

Saying that humans have had an influence does not tell you how big the influence is. With that in mind, we can also conclude:

It is extremely likely that human influence is the main driver of the observed warming.

Using the terminology of the IPCC, *extremely likely* denotes a confidence of 95 percent. So while human influence on the climate system is 100 percent certain (“a fact”), we are 95 percent certain that humans are the main driver – meaning responsible for more than half of the observed warming.

This is still not a terribly precise statement. It only says that we can be very confident that humans are the dominant driver of the warming. However, we can also say:

Humans are likely responsible for 100% of the observed warming since the mid-19th century.

This means that our best estimate is that humans are responsible for all (or nearly so) of the observed warming since the industrial revolution. However, our confidence in this statement is lower – in the IPCC’s parlance, *likely* means about a 66 percent chance the statement is true. To summarize, the scientific community has concluded: (1) it is *certain* humans are influencing the climate, (2) it is *extremely likely* that humans are the dominant cause of the warming since the industrial revolution, and (3) it is *likely* that humans are responsible for all (or nearly all) of the warming.

7.8 Chapter Summary

- To determine a cause for the present-day warming, we examine all of the natural processes that are capable of changing our climate. Plate tectonics and orbital variations can be decisively rejected as explanations for the present-day warming because they are too slow.

Variations in the solar constant can be decisively rejected because we have measurements since the late 1970s and these do not show the Sun getting brighter.

- Unforced variability, such as El Niño cycles, cannot be definitively eliminated as a significant cause of long-term warming. However, there is no theory of how unforced variability could reproduce all of the changes we are observing in the climate system, nor does the climate record prior to industrial human activity show historical evidence of such changes, nor do computer simulations of the climate reproduce them. Given that, the scientific community has concluded this is an unlikely explanation for modern warming.
- There is abundant evidence that the increase in greenhouse gases, which is due primarily to human activities (Chapter 5), can explain the present-day warming. There is strong theoretical evidence that greenhouse gases warm the planet, including the simple arguments detailed in Chapter 4. And sophisticated calculations by climate models are only capable of reproducing the recent warming if the increase in greenhouse gases is included. There is also strong observational evidence that carbon dioxide has played a key role in our climate over the past billion years.
- On the basis of this evidence, the scientific community has concluded that: (1) it is *certain* humans are influencing the climate, (2) it is *extremely likely* (95 percent confidence) that humans are the dominant cause of the warming since the industrial revolution, and (3) it is *likely* (66 percent confidence) that humans are responsible for all (or nearly all) of the warming.

See www.andrewdessler.com/chapter7 for additional resources for this chapter.

TERMS

Eccentricity
 Fingerprints
 Forced variability
 Milankovitch cycles
 Obliquity
 Outlier
 Plate tectonics
 Unforced variability

PROBLEMS

1. (a) List all of the physical processes that can alter the climate.
 (b) For all processes in part (a) except greenhouse gases, explain why they are unlikely to be the cause of the warming over the past few decades.
 (c) List the evidence that greenhouse gases are responsible for the recent warming.

2. In this chapter, we reached three different conclusions about the attribution of recent warming to humans. The three different statements had different levels of uncertainty. What are the statements, and how certain is each one?
3. Why are feedbacks (e.g., increases in water vapor) not discussed as potential causes of climate change?
4. Explain the physical mechanism for the occurrence of ice ages. Make sure you explain the role of carbon dioxide and its timing with respect to the temperature change.
5. Critique this statement: “It is clear that it was warmer around 1000 AD, during the Medieval Warm Period, than it is today. Therefore, humans cannot be causing today’s warming.” Assume that the claim that the Medieval Warm Period was warmer than today is correct (it probably isn’t). Is the logic of this argument correct? Why or why not?
6. What are the three ways that the Earth’s orbit varies? How does each variation affect the climate?
7. Explain how the Paleocene–Eocene Thermal Maximum provides support for the claim that today’s warming is caused by humans.
8. How does plate tectonics affect our climate?

In Chapter 6, we discussed the concept of radiative forcing, which is an imposed change in planetary energy balance. In response, the planet's temperature adjusts so as to restore energy balance, with the climate sensitivity (Section 6.3) determining how much warming is required. Thus, predictions of future climate require predictions of how radiative forcing will evolve in the future combined with an estimate of the Earth's climate sensitivity.

Predicting future radiative forcing basically comes down to predicting how much greenhouse gas and aerosol will be emitted into the atmosphere each year from human activities. Such projections, known as *emissions scenarios*, therefore form the backbone of our predictions of climate change. In this chapter, I describe how they are constructed and what they tell us about our future climate.

8.1 The Factors That Control Emissions

At its simplest, the amount of greenhouse gas released by a society is determined by the total amount of goods and services consumed by that society. This is true because the production of any good or service – be it a car, an iPhone, a university lecture, a cheeseburger, or an hour of tax consulting – requires energy. And energy today is mostly derived from the combustion of fossil fuels, which leads to the release of carbon dioxide to our atmosphere. The emissions of other greenhouse gases and aerosols also generally scale with the amount of consumption, although the causal linkages may not be as direct.

The total value of goods and services produced by an economy is known as the *gross domestic product*, abbreviated GDP. Thus, total emissions by a society are basically set by that society's GDP. If the GDP doubles, then we expect emissions to roughly double. This strong link between GDP and emissions can be seen during recessions. During the economic downturn of the late 2000s, global carbon emissions posted their biggest drop in more than 40 years as the global recession froze economic activity and slashed energy use around the world. As I write this in late 2020, during the coronavirus pandemic, we are experiencing another drop in emissions due to lower consumption of goods and services caused by people staying home.

Rather than consider GDP as a whole, it is useful to break it into the product of two factors: population and affluence. It should be obvious that GDP scales with population. Every person in a society consumes goods and services, so if the population doubles (and everything else remains the same), then total GDP will also double. Emissions will therefore be proportional to population.

In addition to the number of people, how rich each person is also matters because, as people get richer, they consume more. To illustrate the effect of affluence on GDP and emissions, consider three families. The first is a family of four who live as subsistence farmers in sub-Saharan Africa. This family lives in a small one-room house without electricity or running water. They do not own a car and are too poor to buy anything but the bare necessities of life. They farm by hand or with a draft animal. Because the members of this family are so poor and consume so little, they are responsible for little greenhouse-gas emissions.

Now consider a family of four near the bottom of the economic ladder in the United States. They live in an apartment and they own one car. Their apartment is not air-conditioned; they own a television and one or two heavy-duty electrical appliances, such as an oven. Compared with the subsistence farming family in Africa, this family is far richer and consumes far more, and is therefore responsible for more greenhouse-gas emissions.

But their emissions are far below an upper-class family of four in the United States. This family lives in a 4,000 square foot single-family house and owns three cars (for the husband, wife, and a teenage child). The house is air-conditioned and has televisions in almost every room, several computers, VCRs, game consoles, and a rich assortment of electrical appliances. The family flies to several vacation destinations every year. Because of the significant consumption allowed by their affluence, this family is responsible for more emissions than the poorer US family and many, many times the emissions of the subsistence farming family.

This wealth effect leads to enormous disparities in emissions per person. In the United States, emissions were 16.2 tonnes of carbon dioxide per person in 2017.¹ Emissions in China are 6.9 tonnes per person – about 45 percent of US per capita emissions. However, China's population is so large that they nevertheless lead the world in total carbon emissions. Emissions in Nigeria are 0.6 tonnes per person – about one-thirtieth of the United States – reflecting that country's poverty.

Aside 8.1: Units of carbon dioxide emissions

In our discussions of the carbon cycle in Chapter 5, we used gigatonnes of carbon (GtC) as our unit. As we discussed at the time, this unit counts just the mass of the carbon in the carbon dioxide molecule. This is done because the carbon atom is incorporated in different molecules in the different reservoirs: it might be in a carbohydrate molecule when stored in the land biosphere or in a carbonate when stored in the ocean, or a carbon dioxide molecule when stored in the atmosphere. It therefore makes the most sense to consider just the mass of carbon as carbon flows around the reservoirs.

When quantifying emissions of carbon dioxide into the atmosphere, however, the convention is to count the mass of both the carbon atom *and* the oxygen atoms. A carbon atom has an

¹ From <https://ourworldindata.org/per-capita-co2>, retrieved October 16, 2020.

Aside 8.1: (cont.)

atomic weight of 12, while a molecule of carbon dioxide has a molecular weight of 44. Thus, 1 Gt of carbon (GtC) is equal to $44/12 = 3.67$ Gt of CO_2 (Gt CO_2) (remembering that a Gt is a gigatonne, which is a billion tonnes). The difference in these values is the mass of the oxygen atoms.

This means that emissions of carbon dioxide to the atmosphere from human activities, expressed in Chapter 5 as 11 GtC per year, would be expressed in this chapter as 40 Gt CO_2 per year. In the rest of this chapter, we'll use Gt CO_2 as our standard unit for emissions in order to be consistent with the convention of the scientific community.

We need a third factor to convert a level of total consumption, expressed in dollars, to greenhouse-gas emissions. This last factor relates how much greenhouse gas is emitted for every dollar of consumption; it is known as the *greenhouse-gas intensity*. Putting these all together, we can now relate emissions to the factors that control it in a simple equation:

$$I = P \times A \times T \quad (8.1)$$

Here I represents the total emissions of greenhouse gases into the atmosphere (these emissions then cause climate impacts, which is why emissions are represented by the letter I); P is the population, A is the affluence, and T is the greenhouse-gas intensity. The decomposition of emissions into these factors is often referred to as the *IPAT relation* or the Kaya Identity.

The greenhouse-gas intensity term T can be usefully broken down as the product of two terms:

$$T = EI \times CI \quad (8.2)$$

EI stands for *energy intensity* – the number of joules of energy it takes to generate one dollar of goods and services. The EI of an economy is primarily determined by two factors. First is the mix of economic activities that make up the economy. For example, it takes much more energy for a steel mill to produce one dollar's worth of steel than for a university to produce one dollar's worth of teaching. The steel mill must run blast furnaces and other heavy equipment, whereas the university only requires lighting, air-conditioning, computers, and the like. More generally, industrial manufacturing has a higher energy intensity than white-collar service-oriented activities. The more industrial manufacturing an economy has, the higher its energy intensity.

The second factor in determining the energy intensity of an economy is the efficiency with which the economy uses energy. For any economic activity, there are usually several technologies to accomplish it. For lighting, for example, there is the old-fashioned incandescent light bulb (the kind with the filament) or the LED light bulb. As described in Chapter 3, incandescent light bulbs are dreadfully inefficient, requiring 60 W of power

to produce the same light as a LED light bulb drawing 10 W. Both light-bulb technologies can light a room, but they consume vastly different amounts of energy doing it. The trade-off is that better technology is often more expensive. As a result, it takes a certain level of wealth to make an upfront investment in energy-efficient technology that will pay for itself over time. Because of this, the efficiency with which different countries utilize energy can vary greatly.

CI in Equation 8.2 stands for *carbon intensity* – the amount of greenhouse gas emitted per joule of energy generated – which reflects the mix of technologies used to generate energy, i.e., whether the economy uses fossil fuels (coal, oil, gas) or low-emission technologies (nuclear, wind, solar, etc.). Among fossil fuels, combustion of natural gas (methane or CH₄) produces the least carbon dioxide per joule of energy generated. Thus, it has the lowest carbon intensity, which is one of the reasons it is often considered to be the “greenest” of the fossil fuels. Oil produces more carbon dioxide per joule than methane, so it has a higher carbon intensity. The most carbon-intensive fossil fuel is coal – it produces roughly twice as much carbon dioxide per joule as methane – which explains why many people who are concerned with our climate are opposed to the construction of new coal-fired power plants. Energy sources that produce no carbon dioxide, and therefore have a CI of zero, include hydroelectric, nuclear, wind, and solar energy sources.

For a country such as France, which generates most of its electricity from nuclear energy, the carbon intensity will be smaller than for a country such as China or the United States, which both rely heavily on fossil fuels for electricity.

Aside 8.2: Check the units!

One of the most powerful ways to check your work is to make sure that the units in a problem work out. We do this now to close the loop on our understanding of the factors that regulate carbon emissions.

Population is obviously the number of people. Affluence is dollars of GDP per person. The product of population and affluence is therefore GDP, which has units of dollars:

$$\text{Number of people} \times \frac{\$GDP}{\text{person}} = \$GDP$$

Energy intensity has units of joules per dollar, and carbon intensity has units of carbon dioxide emitted per joule. Greenhouse-gas intensity is the product of energy intensity and carbon intensity, and therefore it has units of carbon dioxide emitted per dollar:

$$\frac{J}{\$GDP} \times \frac{CO_2}{J} = \frac{CO_2}{\$GDP}$$

Finally, the product of population, affluence, and technology has units of carbon dioxide emitted:

$$\text{Number of people} \times \frac{\$GDP}{\text{person}} \times \frac{CO_2}{\$GDP} = CO_2$$

8.2 How These Factors Have Changed in the Past

In the last section, emissions of carbon dioxide were deconstructed into the controlling terms: population, affluence, energy intensity, and carbon intensity. Let us look at how these terms have changed over the past few decades and how they might change in the future.

Population: Population has been rapidly increasing for most of human history. Global population reached 1 billion in 1804. The 2-billion-people mark was reached 123 years later, in 1927, and the 3-billion-people mark was reached 33 years later, in 1960. Since then, world population has been increasing by 1 billion people every 12 to 13 years, reaching 6 billion in 1999 and 7 billion in 2011. In mid-2020, when I wrote this, the population was 7.8 billion, and Figure 8.1a shows that this is 2.5 times the value in 1960. Today, world population is increasing by roughly 200,000 people per day, a population growth rate of approximately 1 percent/year. Most of this growth is occurring in the developing world, where fertility rates remain high.

Affluence: Figure 8.1a shows that affluence, measured as GDP per person, also more than doubled since 1960. This reflects my own personal experience. My teenage kids have far more material possessions (computers, TVs, cell phones) than I did as a child, and I had far more than my parents did. My parents, in turn, were far richer than my grandparents.

Energy intensity: The first part of the technology term, the energy intensity term, has markedly decreased over the past half century as our society has developed more efficient ways to use energy (Figure 8.1b). Some of this increasing efficiency has been driven by market forces: Because energy costs money, a more energy-efficient piece of equipment or process will reduce costs, which consumers want. As a result, just about everything you buy today is more energy-efficient than the comparable version of a few decades ago.

Much of this increase in efficiency is incremental, meaning that each new generation of a particular piece of equipment uses slightly less energy than the previous version. Sometimes, however, there is a revolution in technology that greatly reduces energy consumption. A good example is the revolution in lighting technology we are now experiencing. As the world switches from incandescent bulbs to LED lighting, the amount of energy being consumed by lighting will experience a substantial one-time drop.

Changes in the mix of goods and services produced by the world's economy has also led to decreases in energy intensity. Over the past century, the fraction of the world economy based on energy-intensive heavy industry and manufacturing has declined, while the fraction based on services has increased.

Carbon intensity: Figure 8.1b shows that carbon intensity, the amount of carbon dioxide released per joule of energy generated, decreased from 1960 to about 2000 as the world shifted from dirty energy, like coal, to cleaner energy sources, like natural gas. In the 2000s, coal staged a resurgence as China built out their coal fleet to support their rapid economic growth. In the 2010s, however, cheap natural gas from the development of new drilling techniques, in particular hydraulic fracturing (more commonly known as fracking) flooded

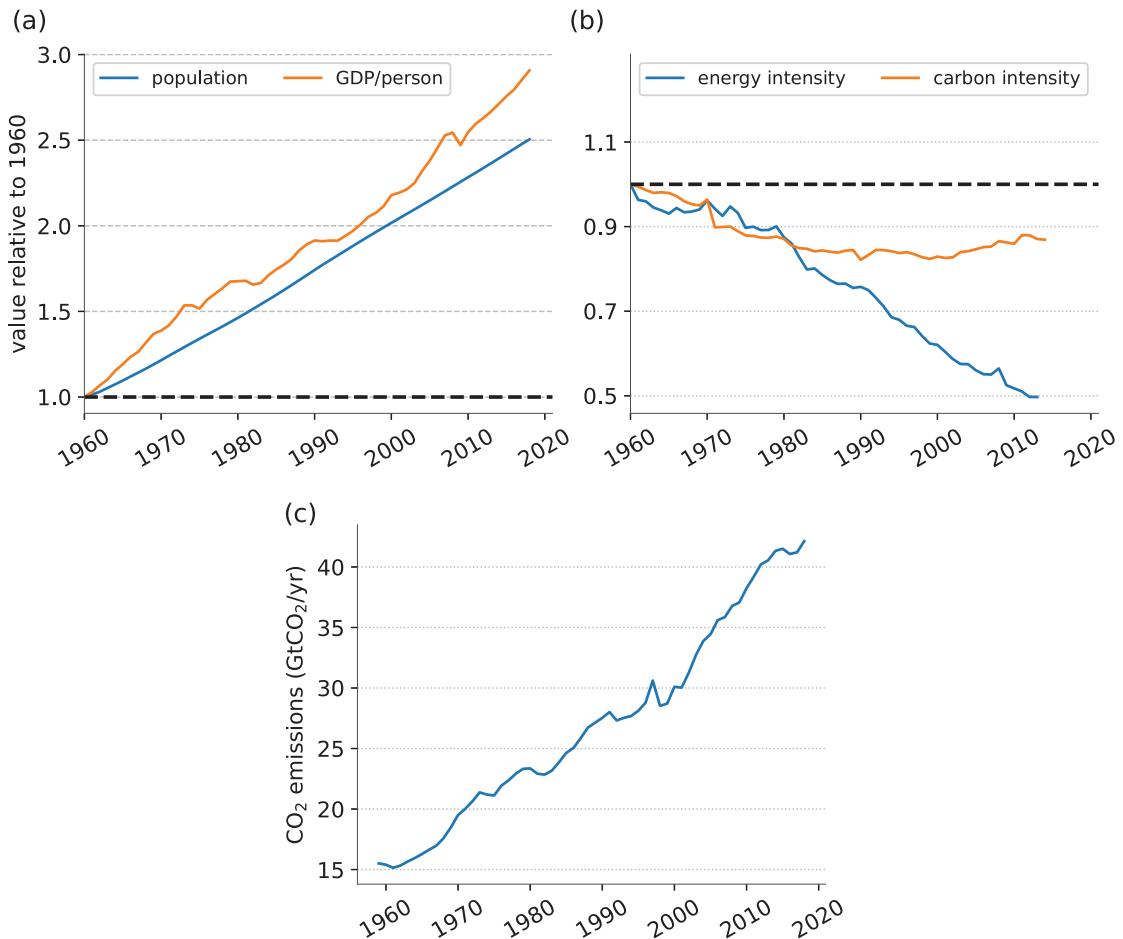


Figure 8.1 (a) Population and affluence (\$/person) values, relative to values in 1960. (b) Carbon intensity (CO_2/J) and energy intensity ($\text{J}/\$$), also relative to 1960. (c) Total emissions of carbon dioxide, in GtCO_2 per year. Data for population, GDP per person, and carbon intensity come from the World Bank, downloaded from <https://data.worldbank.org/>, retrieved June 12, 2020. Energy intensity is calculated from estimates of energy consumed and GDP downloaded from De Stercke, 2014, accessed via <http://tntcat.iiasa.ac.at/PFUDB>, retrieved June 13, 2020. Emissions data are described by Friedlingstein et al. (2019) and were downloaded from www.icos-cp.eu/global-carbon-budget-2019, retrieved June 9, 2020.

the energy market and began displacing coal, thereby reversing the trend towards increasing carbon intensity.

Combining the changes in these terms gives us the overall change in emissions. Over the past few decades, population (P) and affluence (A) have increased faster than energy intensity (EI) and carbon intensity (CI) have declined. This has led to an overall increase in emissions of nearly a factor of 3 between 1960 and 2018 (Figure 8.1c).

8.3 Emissions Scenarios

We can talk about the past all day, but the climate problem is really about the future. If our ultimate goal is to predict the future climate, we first need estimates of how much greenhouse gas human society will emit. That, in turn, requires predictions of the factors that control greenhouse-gas emissions — population, affluence, and technology.

8.3.1 Factors That Drive Emissions

But, as the old saying goes, “It’s hard to make predictions – especially about the future.”² For example, predicting future population trends requires predictions of a range of factors from the rate of poverty to the evolution of religious and social views on birth control, the rate of education of women in high-fertility regions, available healthcare in these regions, and so on.

Because of this, the community of experts does not make a single prediction of the future. Rather, they have 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:³

SSP1: Sustainability. *The world shifts gradually, but pervasively, toward a more environmentally friendly path. The world becomes a more equal place, with economic growth in poor countries causing them to close the wealth gap with the rich world. Population growth is slow, peaking in mid-century, and the world shifts towards renewable energy.*

SSP2: Middle of the road. *The world follows a path in which social, economic, and technological trends are similar to historical patterns.*

SSP3: Regional rivalry. *The rich get richer, but the poor do not, leading to increasing conflict between regions. Nationalism is ascendant. Population growth is low in rich countries, but high in poorer ones. Consumption is resource-intensive and technological development is slow, leading to a reliance on high-carbon-intensity fuels like coal.*

SSP4: Inequality. *Like SSP3, the world is a divided place, but this scenario features more rapid technological development and deployment of energy technologies with low carbon intensities.*

SSP5: Fossil fueled development. *This world is similar to the optimistic SSP1 world, but it is powered by fossil fuels rather than SSP1’s shift towards more sustainable energy. There is an emphasis on economic growth rather than sustainability.*

For each of these narratives, scientists can make predictions of population, affluence, and technology. Population (Figure 8.2a) peaks in mid-century in all SSPs except SSP3. Affluence

² This statement has been attributed to various people, including Niels Bohr and Yogi Berra.

³ These are adapted from Riahi et al. (2017).

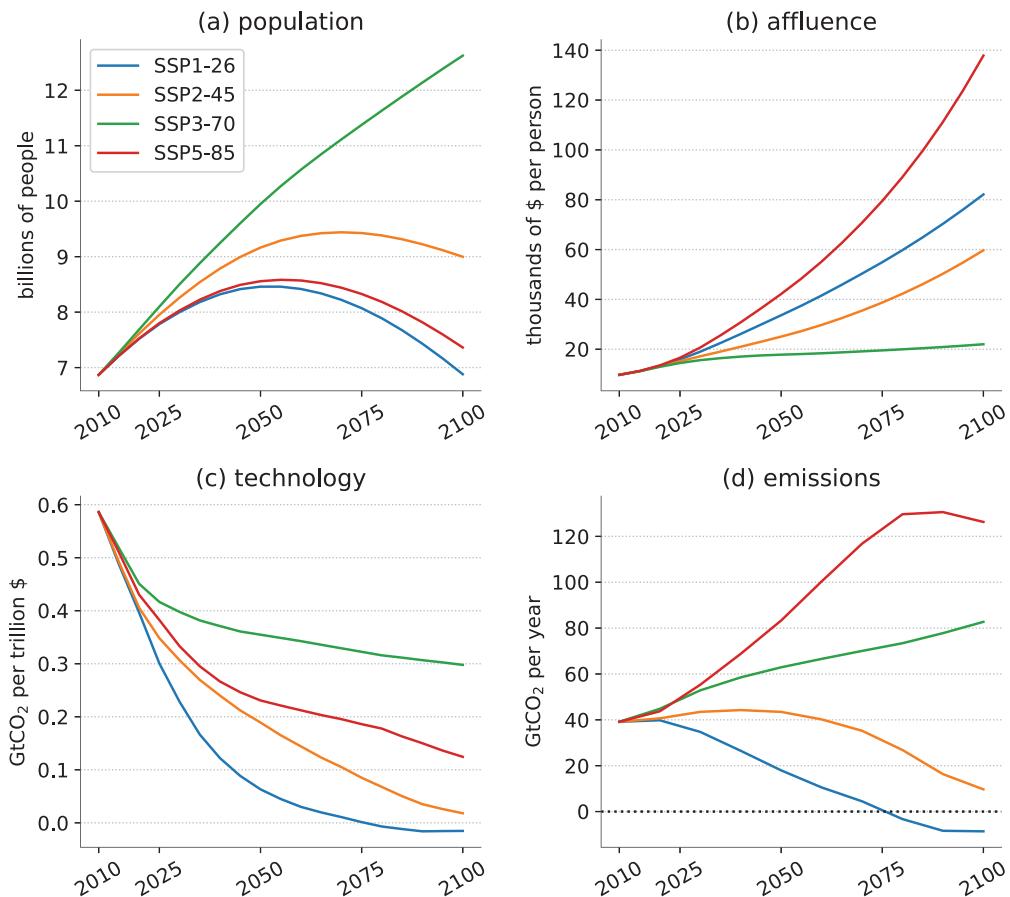


Figure 8.2 (a) Population (in billions), (b) affluence, (dollars of GDP per person), (c) technology term (GtCO_2 per trillion dollars of GDP), and (d) emissions of carbon dioxide (GtCO_2 per year). Data in panels a–c from Riahi et al. (2017), panel d from Rogelj et al. (2018) and Gidden et al. (2019), all downloaded from <https://tntcat.iiasa.ac.at/SspDb>, accessed July 4, 2020.

(Figure 8.2b) increases in all pathways, although there is considerable spread between them. SSP3 has the lowest affluence growth, about 1 percent per year, while SSP5 has the highest growth, about 3 percent per year. SSP1 also features strong growth, but it is lower than SSP5 because the SSP1 world is more focused on sustainability than consumption.

A key feature of these narratives is that they are internally consistent. For example, population growth is connected to affluence, with poor countries having higher fertility rates than rich ones. In extremely poor societies, children can be put to work at a young age and are therefore a source of income. This is generally not the case in rich countries, where children are a net drain on family resources for many years (trust me on that). In addition, high rates of childhood death in poor countries mean that parents must have many children to ensure that some of them survive into adulthood, while in richer countries with better

health care, parents can reasonably expect their children to survive into adulthood. Women tend to get better educated in richer countries, which also leads to declining fertility rates as good-paying jobs become available to women as an alternative to child rearing. Because of this, the scenarios in which the world's poor become richer (SSP1 and SSP5) feature slower population growth than the scenarios in which poverty is maintained (SSP3).

The last thing needed to obtain emissions of greenhouse gases is to determine values for the technology term, which mainly reflect the technology used to produce energy (Figure 8.2c). The units for this term are emissions per dollar, with lower values reflecting more climate-safe energy being used. In all scenarios, this term declines over time as the world relies more and more on climate-safe energy. But the rate of adoption varies significantly between the scenarios. Because the development and deployment of new climate-safe technology take money, such development and deployment are slowest in the low-affluence SSP3 world and fastest in the much richer SSP1 world. But wealth is not the only determinant. The SSP5 world is also a rich, high-growth world, but it is one that nevertheless relies predominantly on fossil fuels, so it has a larger value for this term than the SSP1 world.

8.3.2 Emissions

Given estimates of population, affluence, and technology, we can estimate emissions (Figure 8.2d). The highest emissions scenario is the SSP5, which features both high growth and a reliance on fossil fuels. In that world, 2100 emissions are 126 GtCO₂ per year, about 3 times today's emissions. The SSP3 world is actually a dirtier world, more reliant on fossil fuels. But that world is poorer than SSP5, so total emissions end up being lower. Despite that, SSP3 emissions in 2100 are more than double emissions in the late 2010s.

SSP3 and SSP5 are worlds where it is assumed that no efforts to address climate change are made beyond what the world has already done. SSP1 and SSP2 represent worlds where more strenuous efforts are made to reduce emissions. In SSP2, emissions peak around 2050 and decline thereafter. In SSP1, emissions are peaking around today and decline throughout the rest of the century. In fact, SSP1's emissions go negative around 2075, meaning that humans are pulling more carbon out of the atmosphere than they are releasing. We will discuss these negative emissions and what they mean for climate policy later in the book.

8.3.3 Atmospheric Abundance and Radiative Forcing

Given an emissions scenario, the atmospheric concentrations of carbon dioxide can be calculated by feeding those emissions into a carbon-cycle model. The carbon-cycle model calculates how much atmospheric carbon dioxide is removed by the carbon cycle and how much remains in the atmosphere (this was discussed in detail in Chapter 5).

Figure 8.3a shows atmospheric carbon dioxide abundances over the twenty-first century. As can clearly be seen, the different scenarios correspond to very different atmospheric abundances of carbon dioxide. Given these atmospheric abundances,

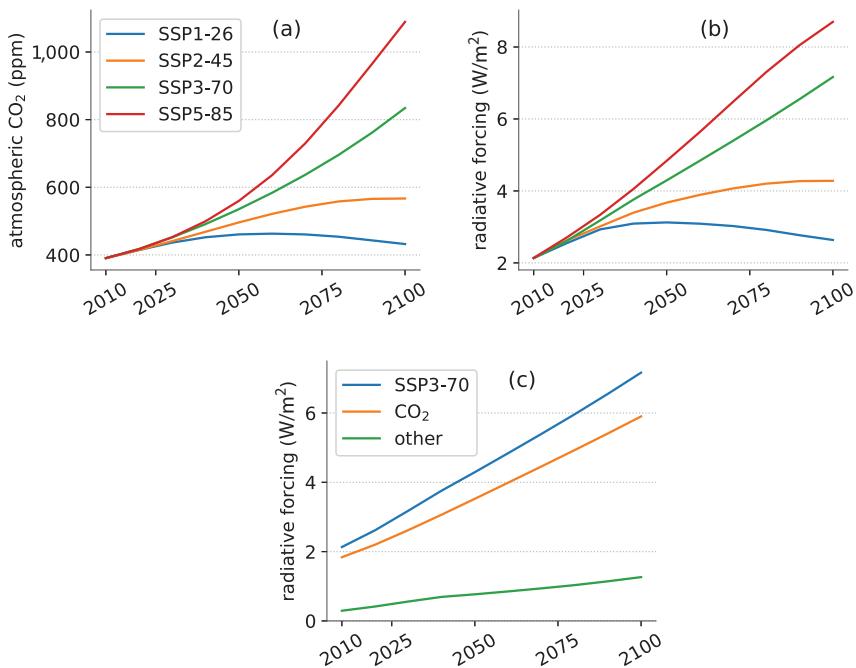


Figure 8.3 (a) Atmospheric carbon dioxide (ppm) and (b) radiative forcing (W/m^2) for four key emissions scenarios, (c) radiative forcing (W/m^2) in the SSP3-70 scenario from all constituents, from just carbon dioxide, and from everything else. This figure is based on the SSP data of Riahi et al. (2017), downloaded from the IIASA Energy Program at <https://tntcat.iiasa.ac.at/SspDb>, accessed July 4, 2020.

along with abundances of other greenhouse gases and aerosols, the radiative forcing can then be calculated. Figure 8.3b shows the radiative forcing predicted for each scenario over this century.

Aside 8.3: How are SSPs named?

Up above, I laid out the storylines for five SSPs, numbered SSP1 through SSP5. But in the figures, the pathways have two-digit numbers appended to them (e.g., SSP1-26). What does the “26” mean? It turns out that each SSP storyline is associated with a large number of possible futures, each with its own emissions profile and associated radiative forcing. There is a baseline scenario, meaning that it contains no climate policy (other than policies already adopted) as well as a number of other pathways that assume different policies to reduce emissions.

Thus, just specifying SSP1, for example, does not tell you which of the SSP1 emissions pathways I’m referring to. This problem is solved by adding the radiative forcing in 2100 to the SSP name. Thus, SSP1-26 is the emissions scenario that follows the SSP1 storyline and that has radiative forcing of 2.6 W/m^2 in 2100. This is just one of a number of SSP1 scenarios having radiative forcing in 2100 ranging from 1.9 W/m^2 to 5.0 W/m^2 .

Aside 8.3: (cont.)

In this book, I refer to the most commonly used emissions scenario from each pathway: SSP1–26, SSP2–45, SSP3–70, and SSP5–85, which have radiative forcings in 2100 of 2.6, 4.5, 7.0, and 8.5 W/m^2 , respectively. The SSP4 pathway is less frequently analyzed, and I won't analyze it further.

Emissions scenarios are updated every decade or so as our knowledge of how society may evolve over the coming century changes. Prior to the SSPs, the set of scenarios used were known as the Representative Concentration Pathways, abbreviated RCPs. The RCPs were estimates of atmospheric concentrations of greenhouse gases over time designed to give particular trajectories of radiative forcing. The key difference from the SSPs is that there are no economic and social drivers associated with the RCPs — they are simply concentration pathways that give particular values of radiative forcing.

There were four main RCP scenarios having radiative forcing values in 2100 of 2.6, 4.5, 6.0, and 8.5 W/m^2 (known as RCP2.6, RCP4.5, RCP6.0, and RCP8.5). The choice of the main SSPs mirrors these values, so the RCP2.6 scenario is comparable to the SSP1–26 scenario, and the RCP4.5 and RCP8.5 scenarios are comparable to the SSP2–45 and SSP5–85 scenarios.

Figure 8.3c shows radiative forcing from the SSP3–70 scenario, along with the radiative forcing broken down into the contribution from carbon dioxide and from everything else. The plot shows that, as we go into the future, carbon dioxide is responsible for most of the increase in radiative forcing. The reason for this is carbon dioxide's long lifetime in the atmosphere (discussed in Chapter 5) – once emitted, carbon dioxide stays in the atmosphere for centuries. So carbon dioxide accumulates in the atmosphere like water in a stopped-up sink, and the radiative forcing from it accumulates too. This explains why there is such a strong focus on carbon dioxide in policy debates over climate change.

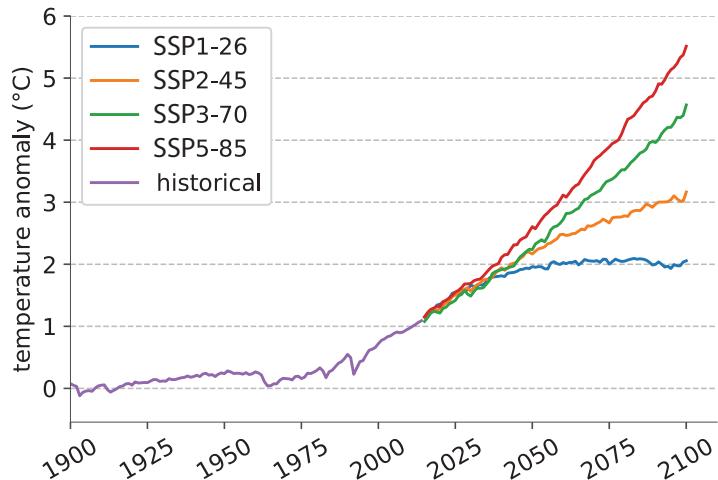
8.4 Predictions of Future Climate

8.4.1 Over the Next Century

The estimates of atmospheric radiative forcing shown in Figure 8.3 can then be translated into projected climate change for each scenario. These are plotted in Figure 8.4, and they show that the set of emissions trajectories translates into a wide range of potential future climates. The large emissions associated with the SSP5–85 scenario lead to temperature increases of 5.5°C above the pre-industrial climate in 2100 (about 4.5°C above 2020 temperature), while the low emissions associated with the SSP1–26 scenario lead to temperature increases of 2°C above pre-industrial temperatures (about 1°C above 2020 temperature).

It is worth noting that, despite huge differences in emissions (Figure 8.2d), the scenarios predict relatively similar warming until they begin to diverge around 2040–2050. This occurs because the lifetime of carbon dioxide is so long that carbon dioxide is essentially just

Figure 8.4 Average of 17 computer simulations of global and annual average surface temperature anomaly under four emissions scenarios. Temperatures prior to 2014 are from model runs driven by historical forcing. Estimates are from the CMIP6 model archive, processed by N. Swart, downloaded from <https://github.com/swartn/cmip6-gmst-anoms>, on October 16, 2020.



accumulating in the atmosphere. The amount presently in the atmosphere is large enough compared to annual emissions that it takes several decades for differences in the scenarios to translate into significant differences in the amount of carbon dioxide in the atmosphere. In 2045, for example, there is a factor of 3 difference between the highest and lowest emissions scenario, but atmospheric carbon dioxide differs by only 16 percent. The upshot is that the temperature trajectory over the next few decades has already been largely determined by emissions that have already occurred.

But Figure 8.4 also clearly shows that we do have significant control over the amount of warming experienced during the second half of the twenty-first century – there is nearly 4°C difference in temperature between the lowest (SSP1–26) and highest scenario (SSP5–85). Many of the people reading this book will live through the second half of the century, so you can look at Figure 8.4 as the range of possible futures you might experience. As we'll talk about in the next chapter, the differences in the impacts of climate change between these possible futures are *huge*.

Aside 8.4: Will the evolution of the climate over the twenty-first century look like the trajectories plotted in Figure 8.4?

If you look at Figure 2.2, you will see that, over the past 130 years, the climate has generally warmed, but it also shows significant year-to-year variability, which is caused by things such as El Niño cycles and volcanic eruptions. Such variability means that temperatures can decline for a few years, even as the climate is experiencing a long-term warming (this was shown in Figure 2.5).

This short-term variability is missing from the projections of the future in Figure 8.4. The reason is that what is plotted in that figure is an average of many computer simulations. Individual computer simulations also show year-to-year variability that is similar to that in the

Aside 8.4: (cont.)

observations. But in the individual simulations going into the average, the highs and lows caused by the short-term variability do not occur at the same time, so when you average many simulations together, as I have done in this figure, the short-term ups and downs tend to cancel out and you get a smooth increase in temperature throughout the century. In reality, short-term variability is going to be important, and we can expect the same kinds of ups and downs seen in the past 130 years to continue to occur in the future.

8.4.2 Climate Change Beyond 2100

Even though Figure 8.4 stops in year 2100, climate change does not stop at that date. In Chapter 5, we talked about the long lifetime of carbon dioxide in our atmosphere: Of carbon dioxide emitted into the atmosphere today, about 25 percent will still be in the atmosphere in several centuries (Figure 5.8), and it will take a hundred thousand years or so to remove all of the added carbon from the atmosphere. The impact of the long residence time of carbon dioxide in our atmosphere can be seen in Figure 8.5a, which shows atmospheric carbon dioxide over the next 1,000 years for emissions scenarios in which atmospheric carbon dioxide increases until it reaches 550, 850, and 1,200 ppm, at which point emissions decline instantly to zero.

After emissions cease, carbon dioxide declines slowly. Even by the year 3000, eight to nine centuries after carbon dioxide emissions ceased, atmospheric carbon dioxide in all scenarios remains well above pre-industrial values (280 ppm). This is simply a reflection of

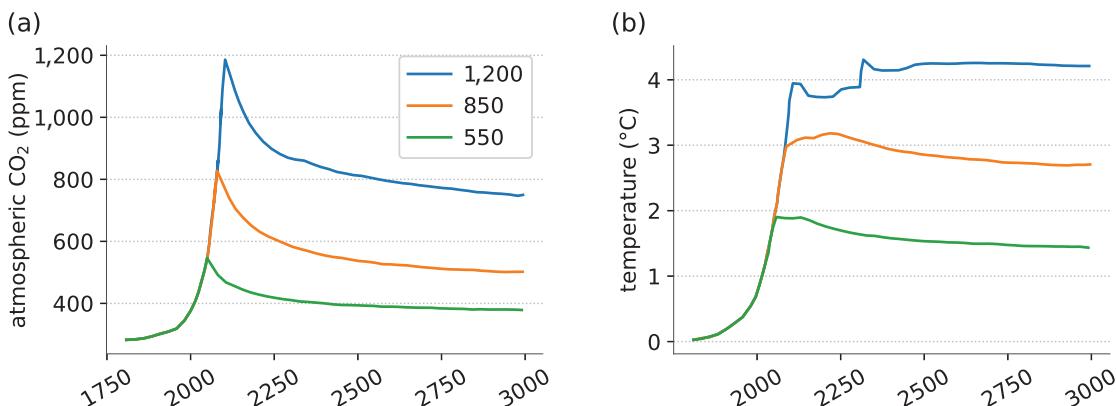


Figure 8.5 (a) Amount of carbon dioxide in the atmosphere as a function of time, for the next 1,000 years. Carbon dioxide emissions rise at 2 percent/year until it hits a peak abundance (550, 850, and 1,200 ppm); then emissions are decreased instantly to zero. (b) The temperature time series corresponding to each carbon dioxide time series. Adapted from Figure 1 of Solomon et al. (2009).

how long it takes for the carbon dioxide we're adding to the atmosphere to be removed by the carbon cycle.

The long-term evolution of temperatures associated with these carbon dioxide time series is shown in Figure 8.5b. Much like carbon dioxide, the temperatures do not significantly decline over the next 1,000 years. This is a consequence of three factors. First, carbon dioxide remains elevated throughout the millennium, so it continues to trap heat for a very long time after emissions stop. Second, the ocean's large heat capacity means that the planet cools off very slowly. This is the flip side of the situation in which the warming lags the carbon dioxide increase – the cooling will lag any decrease in atmospheric carbon dioxide abundance. Third, slow feedbacks, such as the very slow destruction of the planet's big ice sheets, will also act to oppose any cooling.

The important point here is that emitting large amounts of carbon dioxide to the atmosphere this century commits the planet to elevated temperatures for thousands of years. Once the temperatures rise, reducing emissions will not bring the temperature back down quickly. We can therefore think of climate change as being irreversible over any time period that we conceivably care about. This also means that actions we take (or do not take) to curb emissions over the next few decades will essentially determine the climate for thousands of years. It is sobering indeed to realize that people of the year 3000, 4000, or 10 000 AD will be so affected by actions we take today.

8.5 Is the Climate Predictable?

One criticism of climate predictions goes something like this: “We cannot predict the weather next week, so why does anyone believe predictions of the climate in 100 years?” This may sound reasonable, because it is based on the correct observation that weather predictions are only accurate a week or so into the future. However, the argument is built on a fatal flaw – it makes the mistake of equating weather predictions with climate predictions. In fact, it *is* possible to predict the climate in 100 years even if weather is only predictable for a few days.

The root cause of this conundrum is that predicting the weather and predicting the climate are fundamentally different problems. A weather forecast is a prediction of the exact state of the atmosphere at an exact time: “At 8 AM tomorrow, the temperature in Washington, DC, will be 3°C, and it will be raining.” If you get the time of an event wrong – for example, you predict rain for 8 AM but it does not rain until 6 PM – then you have blown the forecast. If you predict rain for the Washington, DC, area but the rain falls 50 km to the west in Northern Virginia, then you have blown the forecast. And if your temperature is off by a few degrees and snow falls instead of rain, and it completely snarls traffic on Interstate 495, then you have *really* blown the forecast.

A climate prediction, in contrast, does not require predicting the exact state of the atmosphere at any particular time; instead, it requires predicting the *statistics* of the weather over time periods of years. Thus, a climate prediction for the month of March for the years between 2080 and 2090 for a particular location might be as follows: average monthly

temperature of 12°C, with an average high of 16°C and an average low of 5°C; monthly average precipitation of 6.0 cm; and so on.

Being unable to predict the exact state of a complex system (e.g., the weather) does not preclude the ability to predict the statistics of the system (e.g., the climate). As an analogy, consider that it is virtually impossible to predict the outcome of a single flip of a coin. However, the statistics of coin flips are well known: If you flip a coin 10,000 times, I can tell you that you will get between 4,918 and 5,082 heads (90% confidence interval). In other words, the inability to accurately predict any single coin flip does not preclude the ability to accurately predict the long-term statistics of the coin.

To make this point more concretely, answer the following question: “Is it going to be hotter in Texas next January or next August?” If you know Texas weather, you can predict with 100 percent certainty that August is the hotter month, and you can make this prediction months, years, or decades in advance. Think about that for a minute: You just made a climate prediction that is valid years in advance – far beyond the ability to predict weather.

More technically, weather forecasts belong to a class of problems known as initial value problems. This means that, to make a good prediction of the future state of the system, you must know the state of the system now. If you have a marble rolling down a slope, and you want to predict where it will be in one second, you need to know where it is now to make that prediction. Similarly, to make a good weather forecast for tomorrow, you have to accurately know the state of the atmosphere today. The state of today’s atmosphere is then input into a forecast model, which turns out a prediction of tomorrow’s atmosphere. However, small errors in our knowledge of today’s atmosphere grow exponentially, so that a forecast more than a week or so in the future is dominated by the errors in our knowledge of today’s atmosphere. That is what sets the range of weather forecasts.

Climate forecasts are a class of problems known as boundary value problems. This type of problem does not require knowledge of today’s atmospheric state but rather requires a knowledge of the radiative forcing of the climate. This is why, for example, we can predict with 100 percent certainty that August in Texas will be on average hotter than January in Texas. We know this because we know that more sunlight falls on Texas and the rest of the northern hemisphere during summer, leading to higher temperatures.

Increases in greenhouse gases also increase the heating of the surface, although by infrared radiation rather than visible. Thus, we can have confidence that, if we add greenhouse gas to the atmosphere, the increase in surface heating will warm the planet – just as we can predict that summer will be hotter than winter.

One should not take this to mean that predicting the climate is an easier problem than predicting the weather, only that they are different problems. Some aspects of the climate problem are, in fact, harder than the weather problem. For example, because weather forecasts cover only a few days, weather models can assume that the world’s oceans and ice fields do not change. Climate models, however, cannot make this assumption, because both the world’s oceans and its ice fields can significantly change over a century. Climate models must therefore predict changes in these and other factors in order to accurately predict the evolution of the climate system over a century.

8.6 Chapter Summary

- Projections of future climate require projections of future emissions of greenhouse gases from human activities. Such projections are known as emissions scenarios.
- The factors that control emissions are population (P), affluence (A), and greenhouse-gas intensity (T). This is expressed by what is known as the IPAT relation: $I = P \times A \times T$, where I is carbon dioxide emissions. Affluence has units of dollars of economic output per person, and greenhouse-gas intensity has units of carbon dioxide emitted per dollar of economic output.
- Greenhouse-gas intensity is the product of energy intensity and carbon intensity. Energy intensity reflects the efficiency with which the society uses energy as well as the mix of economic activities in the society, with units of joules of energy consumed per dollar of economic output. The carbon intensity reflects the technologies the society uses to generate energy, and it has units of carbon dioxide emitted per joule of energy produced.
- Because predictions of the future are so uncertain, scientists have constructed a set of plausible, alternative scenarios of how the world might evolve. Taken as a group, these Shared Socioeconomic Pathways (referred to as SSPs) span the likely range of the future evolution of the world's society. Emissions scenarios have been estimated for each pathway.
- Putting these emissions scenarios into a climate model yields predictions of warming in 2100 of 2.0°C to 5.5°C above pre-industrial temperatures (1°C to 4.5°C above temperatures in the 2010s). Except in the most optimistic scenario, future warming will be much larger than the warming of ~1°C that the Earth has experienced prior to 2020.
- Climate change does not stop in year 2100. Carbon dioxide stays in the atmosphere for centuries after it is emitted, so large emissions of carbon dioxide this century will cause the Earth's temperatures to remain elevated for thousands of years. This means that the decisions we make in the *next few decades* will determine the climate for the next few millennia.
- Even though weather is not predictable beyond a few days, we can nevertheless make climate predictions decades in advance. A climate prediction is a prediction of the statistics of the system. For many complex systems, predicting the statistics is possible even in situations where predicting the specific state of the system is not.

See www.andrewdessler.com/chapter8 for additional resources for this chapter.

TERMS

Carbon intensity
Emissions scenario
Energy intensity
Greenhouse-gas intensity

Gross domestic product (GDP)
IPAT relation
Shared socioeconomic pathways

PROBLEMS

1. (a) Someone asks you about how much the climate will warm over the next 100 years. How do you answer?
(b) What determines whether we are at the bottom end of the range or the top end of the predicted range?
2. (a) Define each term in the IPAT identity.
(b) What are the units of each term? Show how the units cancel so that the *I* term has units of emissions of greenhouse gases.
3. (a) The *T* term can be broken into two terms. What are these two terms, and what are their units?
(b) If we switch from fossil fuels to solar energy, which of the terms changes, and does this term increase or decrease?
(c) If we convert from traditional incandescent lighting to LED lights, which of the terms changes, and does this term increase or decrease?
(d) If we switch from natural gas to coal, which of the terms changes, and does this term increase or decrease?
4. Consider this argument: “We cannot predict the weather in a week, so there is no way we can believe a climate forecast in 100 years.” Is this argument right or wrong? Explain your answer.
5. If we emit significant amounts of carbon dioxide this century, how long will the planet remain warm?
6. Assume population grows at 2 percent per year and affluence grows at 3 percent per year.
 - (a) How fast does the technology term have to decrease (in percent per year) so that total emissions do not change?
(b) How fast does the technology term have to decrease (in percent per year) to reduce emissions by 20 percent in 20 years?
7. Explain how your level of wealth impacts how much emission of carbon dioxide you are responsible for. Where do you think you fall in the spectrum of people on the Earth today? Are you a high-emissions person or a low-emissions person? What could you do to reduce your emissions?
8. In 2002, the Bush Administration set a goal of reducing greenhouse-gas intensity by 18 percent by year 2012. Estimate the historical rate of decline of greenhouse-gas intensity between 1960 and 2000 and determine whether the Bush goal was ambitious or not. Did it represent a real effort to address climate change?

9

Impacts of Climate Change

Before the summer of 2010:

Russia is a northern country and if temperatures get warmer, it's not that bad. We could spend less on warm coats. – Vladimir Putin, President of Russia¹

After the summer of 2010:

Practically everything is burning. The weather is anomalously hot... What's happening with the planet's climate right now needs to be a wake-up call to all of us, meaning all heads of state, all heads of social organizations, in order to take a more energetic approach to countering the global changes to the climate. – Dmitri Medvedev, President of Russia²

You might have wondered as you read the first eight chapters, “OK, the climate is changing because of human activities. Why should I care?” In fact, warmer temperatures might sound good – you might associate them with fun things like vacations at the beach or summer cookouts. But reality is quite different. We rely in important ways on the stability of the climate for things such as food and fresh water.

Most people do not notice this reliance because it has been obscured by two centuries of scientific, technological, and economic advancements. Nevertheless, it is there. And every once in a while, Mother Nature reminds us of the impact of climate on our lives. Whether it's the Russian heat wave of the summer of 2010, forest fires in California or Australia in the late 2010s, or Hurricane Harvey's impact on Texas in 2017, we are learning the hard way that warmer temperatures do not mean tank tops and grilled hot dogs but instead mean economic devastation and suffering.

In this chapter, I cover the impacts of a changing climate. As you will see, the worst-case scenarios are very bad. You may well live through most of the century and, if you don't, your kids and grandkids surely will. So, make no mistake, you have skin in the game.

9.1 Why Should You Care about Climate Change?

In Chapter 8, we saw that if the world does nothing to address climate change, we can expect global average temperatures to increase by a few degrees Celsius during the twenty-first

¹ Quoted in “Nyet to Kyoto, Blow for Campaign as Putin Jokes about Global Warming,” *The Mirror*, September 30, 2003, p. 4.

² Quoted in “Will Russia's Heat Wave End Its Global-Warming Doubts?” *Time Magazine*, August 2, 2010.

century. This may not seem like much warming to you. After all, in many places, the hottest summer days are 50°C warmer than the coldest winter days, and daytimes can be 25°C warmer than the following night. And one day can be several tens of degrees Celsius warmer or cooler than the next. None of those temperature changes are catastrophic, so a change in the global average of a few degrees may sound insignificant.

In this case, however, your intuition is wrong. Although the temperature in any single place can vary considerably by season, by day, and even within a day, the variations tend to cancel when averaged over the entire globe. When you are experiencing the warmth of daytime, someone on the other side of the globe is experiencing the coolness of night. When it is summer where you live, it is winter in the other hemisphere. Heat waves in one location are generally canceled by a cold spell somewhere else.

In other words, the large temperature variations in your locale are nearly completely canceled by opposite variations somewhere else on the Earth. Because of this cancellation, the global average temperature of the Earth is very stable. We saw this in Figure 2.2, which shows year-to-year global average temperature variations of just a few tenths of a degree.

Moreover, seemingly small changes in global average temperature are associated with significant shifts in the Earth's climate. For example, the global annual average temperature during the last ice age was about 6°C colder than that of our present climate. At that time, the Earth was basically a different planet. Glaciers covered much of North America and Europe, leading to a very different distribution of ecosystems, and because so much water was tied up in glaciers, sea level was approximately 100 m (330 ft) lower than it is today.

Thus, warming of a few degrees will remake the planet that we live on. Furthermore, it is not just the size of the warming but the rate of warming that is of concern. It took about 10,000 years for the planet to warm 6°C and emerge from the last ice age, an average rate of 0.06°C per century. The rate of warming predicted for the twenty-first century is a few degrees per century – about 50 times faster. Rate matters because the faster the warming occurs, the less time people and natural ecosystems have to adapt to the changes. If the sea level rises 1 m in 1,000 years, it seems likely that we could adapt gracefully to that change. But a 1-m increase in sea level in a century would be much harder to adjust to, and a 1-m increase in a decade would be a disaster, displacing millions of people and destroying trillions of dollars of infrastructure.

Another argument often made is that a warming of a few degrees should not cause concern because the Earth has gone through such warmings and coolings many times during its 4-billion-year history. This is undoubtedly true, as was discussed in Section 2.3. However, modern human society, with a population of billions, metropolitan areas with tens of millions of people, and reliance on industrial farming and large-scale built infrastructure, is only a century or so old. Over this time, the Earth's climate has been stable, warming by less than 1°C. Human society as we know it has never had to face several degrees of warming in a century, and therefore history provides no reason for us to think adjusting to projected warming will be easy.

Finally, you might be asking, "How do I know that a warmer climate will not be better?" The reason it will not be is because both human society and natural ecosystems have adapted

to our present climate. If the climate changes, then we will be less well adapted to our environment. As an analogy, imagine that you go to the tailor and get a suit fitted exactly to the shape of your body. At that point, no change in your body shape will improve the way the suit fits – for example, either gaining or losing weight will cause the suit to fit less well. In a similar fashion, any changes in the climate, either warmer or cooler, wetter or drier, etc., will result in negative outcomes for human society because of our adaptation to the present climate.

As an example of how we rely on the climate, many structures in Alaska are built on permafrost (ground that remains frozen year-round) with the implicit assumption that the ground will remain frozen. As long as that is true, the structures are stable. If the permafrost thaws, however, the ground softens and can shift, potentially destroying structures (e.g., houses, bridges, roads) built on it. Thus, building on permafrost is a classic example of relying on an unchanging climate. Unfortunately, given the warming in the Arctic over the last century, assuming permafrost remains frozen is turning out to be a bad bet.

Agriculture provides another example of adaptation to our present climate. We farm where the climate provides suitable growing-season temperature and precipitation. Around these farms we build essential infrastructure to support agriculture: grain silos, processing plants, tractor dealers, seed suppliers, and cities for all of these people to live. If the climate shifts, and the temperature and precipitation are no longer conducive to farming, all of these investments to support agriculture will no longer be useful. We may have to abandon them and rebuild the infrastructure in whatever region becomes conducive to farming.

Not every single change in every region will be negative. Reductions in extreme cold events will have benefits: less cold-weather mortality, fewer freezing events (which can destroy some crops). Plant growth may well be enhanced in some regions. But these positive effects are expected to be outweighed by the more pervasive negative effects.

The upshot of this discussion is that, when it comes to climate, *change is bad*.

9.2 Physical Impacts

In this section, I will go over a few ways that the physical climate system has been changing and will continue to change.

9.2.1 Temperature

Although the global average temperature is currently increasing and is certain to continue increasing from each decade to the next, warming is not uniform across the globe. Figure 9.1 shows the distribution of future warming under a low and a high emissions scenario. In a continuation of the observed patterns (Figure 2.3a), we see continents warm more than oceans and more warming in the northern hemisphere than in the southern.

We also see that, under both the low and high emissions scenarios, the temperatures in the 2040s are quite similar. As mentioned in the last chapter, this occurs because the lifetime of

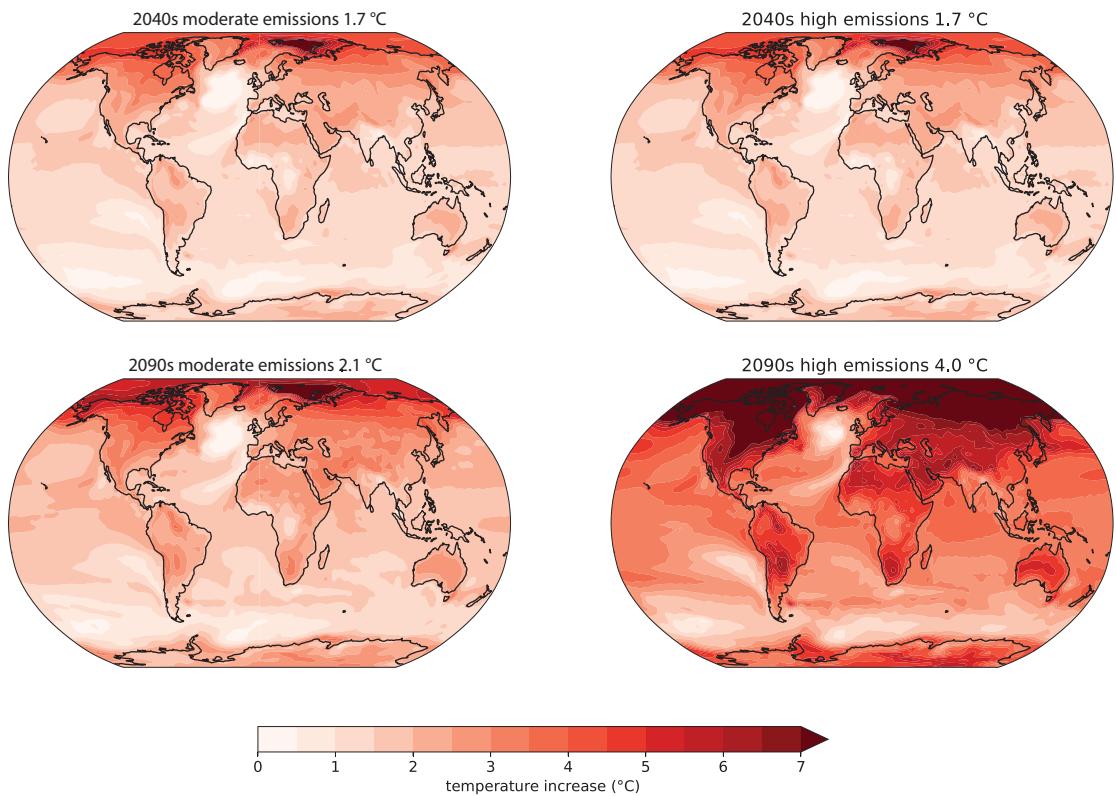


Figure 9.1 The distribution of annual-average warming in the 2040s (top row) and the 2090s (bottom row) for a moderate emissions scenario (RCP4.5, left column) and a high emissions scenario (RCP8.5, right column). Temperature increases are relative to the 1859–1880 average. These are averages of 19 members of an ensemble of climate model runs (Maher et al., 2019).

carbon dioxide is long, so carbon dioxide is essentially just accumulating in the atmosphere. As a result, it takes a while for differences between the emissions scenarios to lead to significant changes in the amount of carbon dioxide in the atmosphere. So even though emissions in the 2040s might be quite different between the low and high emissions scenarios, the amount of carbon dioxide in the atmosphere in the two scenarios is similar, and so therefore is the temperature. Thus, for the next few decades at least, our climate is already largely determined.

While we have limited ability to influence the climate over the next few decades, Figure 9.1 shows that actions we take will have an enormous impact on the climate in the 2090s. There is, of course, uncertainty in the exact magnitude of the warming, both from our understanding of the climate system and from uncertainty in the amount of greenhouse gases we dump into the atmosphere. In addition, unforced variability may distribute the warming in slightly different ways. But we can be confident that the general distribution of the warming will be in accord with these model predictions because they are based on simple physical principles.

Figure 9.1 shows average temperature change. However, many of the negative impacts of a warmer climate come from increased occurrence of extreme temperatures. For example, during the summer of 2003, a heat wave struck Europe in which the average summer temperature in Europe was 3°C above average. Despite this seemingly small amount of warming, this heat wave caused tens of thousands of excess deaths.

Figure 9.2 shows the distribution of daily minimum and maximum temperatures from a computer simulation of July for an area around San Antonio, Texas during two periods, 2015–2019 and 2090s. The simulation assumes a high emissions scenario in which the Earth warms 2.5°C between the 2015–2019 period and 2090s, about twice as much warming as we've already experienced since pre-industrial times. The average July warming in this location in the 2090s is 3.7°C (6.7°F), much larger than the global and annual average, consistent with larger warming over northern hemisphere land.

Figure 9.2 shows that the distribution of both minimum and maximum temperatures has shifted to warmer temperatures. This means that extreme warm temperatures will occur much more frequently. Of particular note, temperatures that never occurred in the 2015–2019 period will become commonplace in the future: The daily minimum in July in the 2015–2019 period never exceeded 29°C, whereas in the 2090s, the July daily minimum exceeds this value 39 percent of the time.

The daily maximum temperature in July never exceeded 39°C in the 2015–2019 period, while in the 2090s, the July daily maximum exceeds this 55 percent of the time. We already see this happening in the historical record, where temperatures that never occurred in past decades now occur regularly (e.g., Figure 1.1).

9.2.2 Precipitation

As greenhouse gases and surface temperature increase, 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 a few percent for every degree Celsius of global average warming.

However, the increase will not be distributed evenly. Predictions of the spatial pattern of changes in annual average precipitation rate in the 2090s are shown in Figure 9.3a. Scientists often refer to this pattern as “wet gets wetter, dry gets drier,” meaning that regions that get a lot of rain today will tend to get more in the future, while places that are dry today will get drier in the future.

Figure 9.3b shows the average change in precipitation rate as a function of latitude. Precipitation increases at most latitudes, with the obvious exception being 30° in both hemispheres, a region that sees a clear decrease. This latitude is already dry – most of the world's major deserts are located around this latitude – so it is consistent with the dry getting drier. The comparison of different emissions scenarios in Figure 9.3b shows that these changes get larger as warming increases.

In addition to changes in the pattern of precipitation, more rainfall will fall in the heaviest downpours, which continues a trend observed over the last few decades. During a heavy

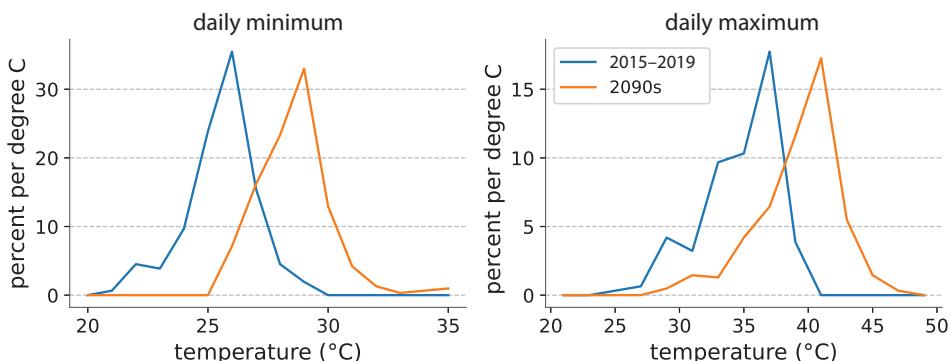


Figure 9.2 Frequency of occurrence of (left) daily minimum and (right) daily maximum temperatures in July for the region around San Antonio, Texas for two time periods: 2015–2019 (blue) and 2090–2099 (orange). Data from a computer simulation by the GFDL-ESM4 model driven by the SSP3-70 scenario. Data were downloaded from the CMIP6 archive (<https://esgf-node.llnl.gov/search/cmip6/>, accessed July 30, 2020).

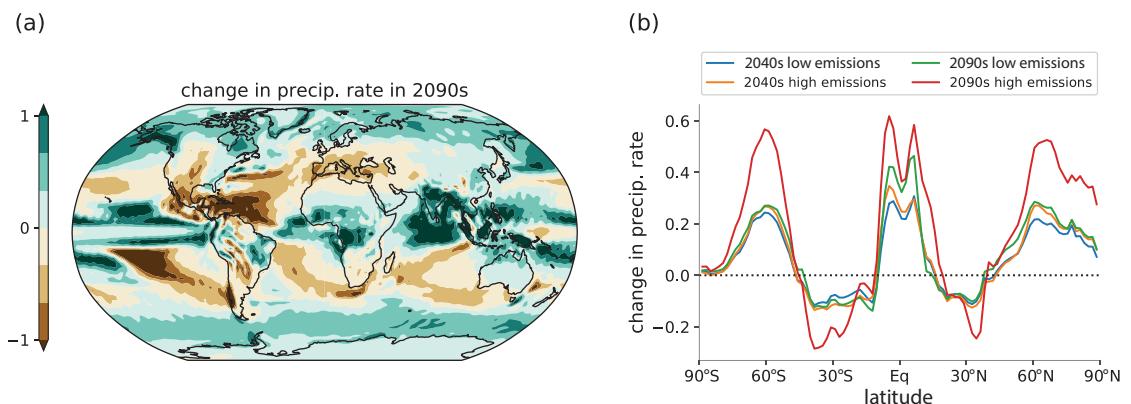


Figure 9.3 (a) Change in annual mean precipitation rate (mm/day) in the 2090s relative to the 1859–1880 period predicted by a climate model driven by a high emissions scenario (RCP8.5). (b) Change in precipitation rate as a function of latitude in the 2040s and 2090s under a moderate emissions scenario (RCP4.5) and a high emissions scenario (RCP8.5), also relative to the 1859–1880 period. Values in both panels are the average of 19 members of an ensemble of climate model runs (Maher et al., 2019).

downpour, the soil saturates before the end of the rain event, and the remaining rain runs off, leading to a number of negative consequences, such as increased risk of flooding and loss of fresh water for use by humans and natural ecosystems.

An increase in the fraction of heavy events also tends to increase the time between rain events. Combined with warmer temperatures, which will increase the rate at which water is lost from soils by evaporation, this is expected to increase drought occurrence. Thus, we get

the surprising result that both wet and dry extremes will grow more likely in the future: wet extremes, with associated risks of flooding, increased erosion, and landslides; and dry extremes, with associated risks of water shortages and drought.

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

Aside 9.1: How do computer simulations work?

Many of the results in Chapters 7, 8, and 9 come from computer simulations of the climate. These are produced by what are known as *global climate models*, frequently referred to by the initials GCMs.³ GCMs have been making predictions of future climate for decades, long enough that we can test how well they do. The answer is quite well – analysis of predictions made decades ago shows that they accurately predicted the future climate.⁴ From a more personal perspective, I've spent a good fraction of my career looking at the output of GCMs, and I am always impressed at how well they simulate our climate system.

The way GCMs work is that they break the atmosphere down into boxes that are tens of kilometers in the latitude and longitude directions and a kilometer or so in height – this discretization of the atmosphere is often referred to as the model's "grid." Models then assume that each box is a uniform chunk of the atmosphere and use the laws of physics (conservation of energy, momentum, and mass) to calculate how the climate in each box evolves over time given the level of radiative forcing from a particular emissions scenario. Even with such a coarse grid, there are about a million grid boxes making up our atmosphere, so predicting the evolution of our climate system over decades requires using some of the biggest supercomputers on Earth.

Many processes in our atmosphere occur on scales comparable to or larger than these grid boxes, and those processes can be directly simulated by GCMs. This includes the large-scale flow of atmospheric winds or the pattern of surface temperature. There are some processes, however, that occur on much smaller scales than the model's grid boxes. Clouds and precipitation are good examples. Clouds are a few kilometers in size, and they are composed of an enormous numbers of individual droplets tens of microns in diameter. Directly simulating the physics of clouds droplets would require breaking the atmosphere down into boxes just microns across. This is completely impossible given available or even imagined computing technology.

But these processes must be included in GCMs for them to accurately simulate our climate. To do that, we rely on *parameterizations*. Parameterizations relate small-scale processes that

³ GCM can also stand for General Circulation Model since it simulates the three-dimensional structure of the atmospheric circulation.

⁴ Hausfather et al. (2020).

Aside 9.1: (cont.)

the models cannot directly simulate, like the interaction of droplets in clouds and the evolution of cloud cover, to things that the model can simulate, such as average temperature and water vapor in that box. Because these parameterizations are usually empirical relations, they typically need to be tuned in order for the model to generate a realistic climate.⁵ This is why parameterizations are generally considered to be the weakest and most uncertain part of computer simulations of the climate.

Precipitation, which occurs when cloud droplets coalesce and become large enough that they begin to fall at significant speeds, is one of the most important processes that relies on parameterization. Other important processes that must be parameterized include changes in clouds, sea ice, vegetation and other land-surface processes, and turbulent processes in the atmosphere.

Because rainfall must be parameterized (see Aside 9.1), predictions of future precipitation patterns (like Figure 9.3) are considered less certain than predictions of temperature (like Figure 9.1), which are mostly based on processes directly represented by the physics of the climate model. Nevertheless, we should have confidence in the general aspects of the models' predictions of precipitation. For example, climate models robustly predicted that intense rainfall would become more common, a result subsequently verified by observations. Such successful predictions indicate that climate models know something fundamental about how rainfall will change as the climate warms. While not every prediction will turn out to be correct, we ignore predictions from climate models at our peril.

9.2.3 Sea-level Rise

Sea-level rise is a 100 percent certain impact of climate change. As we learned in Chapter 2, the sea rises in response to warming temperatures for two reasons. First, as grounded ice melts, the melt water runs into the ocean, increasing the total amount of water in the ocean and, therefore, sea level. Second, like most things, water expands when it warms, which also tends to raise sea level. Measurements (e.g., Figure 2.9) confirm that sea levels have been rising as temperatures have gone up, and we can be certain that the seas will continue to rise into the next century.

Scientists predict that sea level will rise 47 to 73 cm (19 to 29 inches) above 1995–2014 levels by 2100. This may not sound like a significant challenge, but it is much larger than the 18 cm of sea level experienced over the twentieth century, which is already challenging for many who live near sea level.

Like temperature, these predictions of sea-level rise might sound small but, also like temperature, they are not. In Florida, for example, a sea-level rise in the middle of the projected range would inundate 9 percent of Florida's current land area at high tide.⁶ This

⁵ Schmidt et al. (2017).

⁶ See Stanton and Ackerman (2007).

includes virtually all of the Florida Keys as well as 70 percent of Miami-Dade County. Almost one-tenth of Florida's current population, or nearly 2 million people, live in this vulnerable zone, and it includes residential real estate valued at hundreds of billions of dollars. It also includes important infrastructure, such as two nuclear reactors, three prisons, and 68 hospitals. And this is just Florida. Multiply these impacts to account for all of the places on the planet where people live near sea level, and you can get a feel for how big a problem this is going to be.

But this is just the beginning. Over thousands of years, the sea can rise much more, mainly owing to melting of grounded ice. To get a more quantitative estimate of how big that increase might be, we can examine previous changes in climate. During the last ice age, which was 6°C colder, sea level was about 100 m (~300 ft) lower, mainly from the transfer of ocean water to continental ice sheets. During the Eocene, 55 million years ago, the climate was about 15°C warmer and the seas were 80 m higher, mainly because there was little to no permanent ice anywhere on the planet. This gives us a rough rule-of-thumb that we can expect a few meters of sea-level rise for every 1°C of warming.

Given these numbers, the 1°C of warming we have already experienced means that we are *already* committed to several meters of sea-level rise. So why are we only predicting 1 m of sea-level rise over this century, when temperatures might rise several degrees Celsius? The reason is that it takes a very long time to melt ice. If you take an ice cube out of your freezer and put it on your counter, it does not melt instantly even though the room is well above freezing. It may take tens of minutes for the ice cube to melt. Similarly, ice sheets do not respond instantly to increases in temperature. It may take millennia for sea level to fully respond to the warming of the twenty-first century.

Put another way: If we experience several degrees of warming this century, we will commit the planet to many tens of meters of sea-level rise over the coming millennia. While we won't live to see it, nor will any near descendant of ours, it will nevertheless irreversibly alter the shoreline of the planet, for a very long time. People alive in 5,000 years may be living in a world with much higher sea levels owing to decisions you and I make in the next decade or two.

9.2.4 Ocean Acidification

Ocean acidification is another 100 percent certain consequence of emissions of carbon dioxide to the atmosphere. As I explained in Chapter 5, a significant fraction of carbon dioxide emitted to the atmosphere by humans ends up in the oceans where, in the liquid environment, carbon dioxide is converted into carbonic acid (Equation 5.3). The net result is that, as the oceans absorb more and more carbon dioxide, the oceans will become more and more acidic.⁷ Because of emissions that have already occurred, surface-water pH, a measure

⁷ The present pH of the ocean is approximately 8, meaning that it is a base. Acidification here means that the pH is decreasing, not that the ocean will actually become acidic. For the ocean to become acidic, its pH would have to drop below 7, which is very unlikely.

of acidity where lower values mean more acidic, has not been as low as today in the last 2 million years. And this will continue as long as humans are burning fossil fuels.

This can have important impacts on ocean ecosystems. Decreasing the ocean's pH reduces the availability of carbonate ions, making it harder for calcifying critters to build and maintain their shells and skeletons. These species will at first find it more difficult to extract carbonate from the water for use in their shells or skeletons. Eventually, the acidity will increase to the point where it is fatal for these species. It is important to realize that ocean acidification is not just a theory – it has happened before. During the PETM, a massive amount of carbon was emitted into the atmosphere, which subsequently dissolved into the ocean. That event was accompanied by an acidification of the ocean that dissolved much of the carbonate sediment there (Figure 7.8).

9.2.5 Hurricanes

One topic of great interest is tropical cyclones, which are referred to as hurricanes, typhoons, or cyclones depending on which ocean the storm appears in. These are some of the most dramatic weather events we face, and they can cause enormous damage around the world every year. How will tropical cyclones and their impacts change as the climate warms? First, we can say with certainty that tropical cyclones are becoming more destructive because their *storm surge* is getting worse. Storm surge is the wall of water that the storm blows onto shore – imagine a 5-m wall of water coming ashore at the speed of a freight train and it is not hard to see how it can destroy entire seaside communities. As sea levels rise, which is already happening because of climate change and will continue to occur, storm surges will become bigger and more destructive.

There is also high confidence that rainfall from tropical cyclones will increase as the climate warms. This is a consequence of more evaporation from warmer oceans. This in turn leads to more moisture flowing into the storm and, since moisture that flows into the storm eventually comes out as rain, an increase in rainfall.

We have moderate confidence that the number of tropical cyclones will stay roughly the same or may even decrease as the climate warms. That is the good news. The bad news is that we also have moderate confidence that the tropical cyclones that do form will be more intense. Given that most of the damage from hurricanes comes from the most intense storms, this suggests another way that the amount of damage from hurricanes might increase significantly.

9.2.6 Attribution Science⁸

After every weather disaster, someone asks, “Did climate change cause this?” In the most literal sense, that answer is almost always no. Climate change is never the sole cause of

⁸ I thank my colleague, Prof. John Nielsen-Gammon, for his help on this section.

hurricanes, heat waves, droughts, or any other disaster, because weather variability always plays a role in the genesis of the events. However, climate change can make these events worse and, over the last two decades, a new field of science, known as *extreme-event attribution*, has begun to give us the capability to quantify climate's role.

There are various ways to do the analysis. If you have good enough observations of the climate over a long enough period, the data set can be statistically analyzed to determine the likelihood that an observed extreme event occurring today could have occurred prior to human-induced warming.

But even if the observations are good enough for that sort of analysis, they usually can't tell you whether an observed trend was caused by global warming or by something else because correlation does not prove causality. That's where computer simulations of the climate made by GCMs come in. The most common approach is to produce two different simulations of the climate: One simulation is of the real world, so it includes increasing greenhouse gases and a warming climate. The other simulation is what's known as a counterfactual world – an imaginary world in which humans are not adding greenhouse gases to the atmosphere, so the climate is not warming.

Let's imagine that we're analyzing a heat wave in a particular region to determine whether climate change played a role. First, the ability of the GCM to accurately simulate the overall statistics of the temperature of the region must be verified by comparing the statistics of the real world to the statistics of the simulation of the real world. Once the ability of the GCM to simulate our climate is established, the simulation of the counterfactual world is analyzed in order to determine how often the heat wave occurs in a world without global warming. If we find that the heat wave rarely or never occurs in the counterfactual world, then it increases our confidence that climate change was a causal factor in the event.

A final piece of evidence is our understanding of the physics of the phenomenon. It should be obvious to readers of this book why, in a warmer world, we expect to get more frequent heat waves. This physical understanding adds to our confidence that climate change is a factor in the occurrence of heat waves. For other things, such as tornado occurrence or severity, we do not have a simple understanding based on the laws of physics that gives us insight into how they will evolve in a warming world. This lowers our confidence that any particular tornado outbreak was affected by global warming.

Extreme-event attribution studies typically frame their conclusions in one of two ways: either in terms of the fractional contribution of climate change to the extreme or in terms of the change in probability of the event occurring. For example, Hurricane Harvey was an intense hurricane that struck southeast Texas in August 2017 and dumped over 1.5 m of rain on the region. Attribution studies of the storm concluded that climate change increased the storm's total rainfall by about 15 percent,⁹ or, equivalently, made the event about three times more likely to occur.

⁹ van Oldenborgh et al. (2017).

To summarize, there are three possible lines of evidence we can use to determine the role climate change played in a weather event: observed trends in the data, GCM experiments, and physical understanding. If you've got all three (e.g., 2003 European heat wave), you can be confident that climate change made the event worse. If you have zero (e.g., tornadoes), you can't confidently conclude anything – at least for now. The evidence for most types of extreme events is somewhere in between.

Attribution studies are now carried out for most extreme weather events around the world and, while not every event has a strong contribution from global warming, they frequently find that climate change contributed to the extreme. It is therefore correct to say that *climate change is already making many extreme weather events more extreme*.

Aside 9.2: The public debate over the cause of disasters

In the aftermath of horrific forest fires in California during the summer of 2020, an ardent debate about the causes of the disaster ensued. The Trump Administration and its allies claimed that forest management was the reason the fire season was so bad. And they had a point: For decades, forest management policy was to put out fires as soon as they started. This suppression of small fires led to the buildup of flammable material in the forests, meaning that, when a fire did start, there was a lot more material to burn, and the fires could quickly rage out of control.

On the other side were those who claimed that climate change was the cause. They also had a point: Global warming drives warmer temperatures, which tend to dry out vegetation so that fires are easier to start and burn more efficiently once a fire starts.

In reality, both sides were correct. The policy of immediately putting out every fire did indeed cause flammable material to build up, contributing to the ferocity of the fires. But the science is clear that climate change contributed by drying out vegetation, which also made the fires more severe. Random weather variability also played a role: The timing of rainfall during the winter and spring generated a lot of vegetation, which then dried out and built up the fuel load going into fire season.

Thus, arguing over whether the fires were either 100 percent caused by climate change or 100 percent caused by other factors is an intellectual dead end. Disasters have multiple causes, and climate change is usually only one. In some cases, climate change is the dominant cause of the disaster; in other cases, it's a minor contributor. But whatever it's doing today, this is just a small preview of what it will do in the future as the climate continues to warm.

In this section, I've described just a few of the most important ways that climate change will affect the world around us. These are not speculative: Climate change is already making weather disasters worse. In the next section, I will discuss how this impacts human society and the things we care about.

9.3 Impacts of These Changes

As described in the previous section, climate change will bring about a set of certain impacts on our climate system (e.g., increasing temperatures), as well as a host of potential ones (e.g., more intense hurricanes). These will fundamentally change the world, just as they did when the climate transitioned out of the last ice age to the present interglacial. For some people, the potential for rapid, massive changes in the planet is sufficient for them to support policies to stop human-induced climate change. Others, however, view changes in the environment, however regrettable they may be, as a side effect of humanity – we've been doing it in many ways for thousands of years, after all. For them, climate change is a problem because of its impact on humans. In this section, I'll describe how climate change will degrade human welfare – and in some cases is already doing so.

9.3.1 Non-linearity of Climate Impacts

As described in the previous section, we can be confident that humans are making extreme weather events more frequent and intense. And there are good reasons to believe that, as the climate warms, things are going to get a lot worse. If this worries you, join the club – it worries me a lot.

But perhaps you're not terribly worried. The climate has already warmed 1°C, and it's likely that nothing too bad has happened to you yet. You might therefore conclude that climate change *is* a problem – but not for you right now. Perhaps it is causing other people problems now, and it may cause problems for you at some point in the future, but you can worry about it later.

This view fundamentally misunderstands how climate impacts us. For individuals, it is not true that, as the climate warms, things slowly but steadily get worse year after year until, after many years, the sum of the small yearly impacts adds up to a large impact. Rather, the damages are strongly *non-linear*, meaning that things don't get progressively worse in a predictable, straight line.

Rather, things are fine until they're not. For example, Figure 9.4a shows a schematic of how increasing rainfall can impact an individual. At low and moderate rates, the rainfall does no damage because existing infrastructure is capable of handling the runoff. As the rate of rainfall increases, however, it eventually overwhelms existing infrastructure – and large damages can quickly occur.

The key here is that climate change affects individuals *after it passes a threshold*. If you own a house, heavy rain has zero impact until the water reaches your front door. As soon as the water rises enough that water enters the house, you go from zero damage to tens of thousands of dollars of damage essentially in an instant.

As an example, Figure 9.5 shows the value over time of a house near where I grew up in Houston. From 2000–2015, the value of the house increased from \$400,000 to \$700,000. Two massive rainfall events in 2015 and 2017 flooded the house, and in the next few years

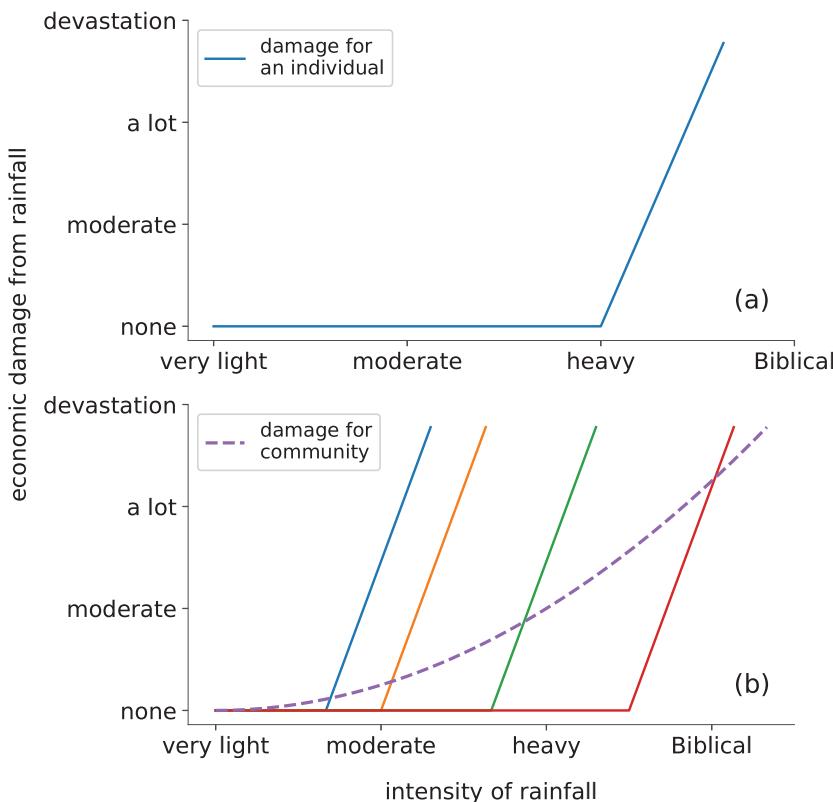


Figure 9.4 (a) A schematic showing the non-linear impact of increasingly intense rainfall for an individual. Increases in rainfall intensity have little impact until they cross a threshold of resilience; increases beyond that produce rapidly increasing damage. (b) A schematic showing the non-linear impacts on several individuals with different thresholds in a community (solid lines), as well as the damage function for the entire community (dashed line).

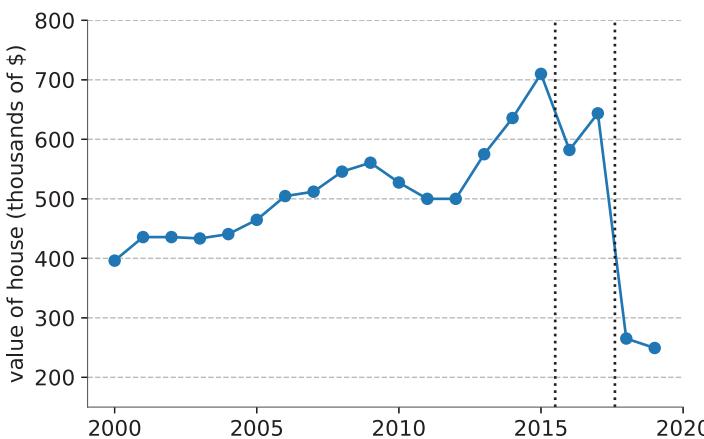


Figure 9.5 Property values for a house in the Meyerland section of Houston, TX. Data obtained from Zillow.com. The dotted lines indicate the dates of two massive flood events that inundated the house.

the house's value dropped by nearly \$500,000. It is important to realize that climate change had been making rainfall more extreme for decades. But it was only in 2015 that the rainfall exceeded the threshold needed to inundate the house. Once that happened, the value of the house plummeted.

In 2014, the owners of the house may have been thinking that climate change was not a big deal. However, in 2020, they know differently. So if you're thinking climate change is a distant problem, you may be right. On the other hand, you might be on the precipice of experiencing an impoverishing climate event, like the owners of the house.

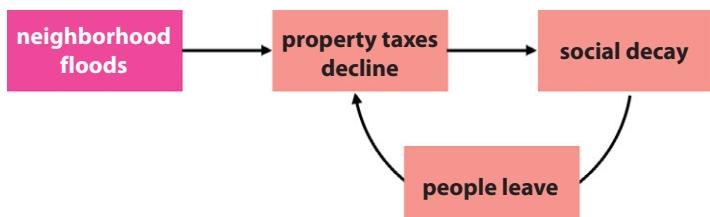
For individuals, climate impacts come on suddenly when thresholds are passed. Communities are an assemblage of individuals with different climate-impact thresholds (Figure 9.4b). Some members of the community are very vulnerable to even small increases in rainfall, while others are invulnerable except to the largest increases. Because of that, every intensification of rainfall will push some additional members of the community past their climate thresholds. The first bit of climate change will push the most vulnerable past their threshold, the next bit will push the next most vulnerable, etc.

Thus, at the community level, you see climate impacts increasing smoothly as the climate changes (Figure 9.4b). The damage curve bends upward, meaning each unit of climate change will cause a larger increase in impacts on our society than the previous unit of climate change. This should be intuitively obvious: The first inch of rain from a hurricane brings little damage, the second inch brings slightly more damage than the first inch, while the 60th inch brings terrible consequences.

Climate impacts can be socially destabilizing. For example, property taxes are assessed based on the value of the property, so as the value of homes in a community goes down in response to this hypothetical flood, the taxes collected go down, too. These property taxes fund things like schools, fire departments, hospitals, and roads, so a reduction in property taxes means spending on these things goes down – schools get worse, hospitals can't hire as many doctors and nurses, and roads don't get fixed. No one wants to live in a place that's falling apart, so the decline in property taxes causes people to flee the community, further driving down property prices, which further drives down property taxes, leading to more social decay and more people leaving – this is a feedback loop, diagrammed in Figure 9.6, similar to the ones we talked about in Chapter 6.

Eventually, the only people left are those too poor to move. At this point, the community has essentially disintegrated. In this way, your house need not flood for you to be affected. If the houses of everyone around you flood, and the neighborhood starts to decay, then your house will certainly lose value.

Figure 9.6 A feedback loop, initiated by flooding, leading to disintegration of a neighborhood.



9.3.2 Adaptation

As the climate changes, humans can and will adapt to it. For example, many of the houses in the neighborhood around the house in Figure 9.5 are currently being lifted a few meters off the ground (this costs about \$70 per square foot, so lifting a 2,500 sq. ft house would cost \$175,000) or are being torn down and rebuilt higher off the ground. So we can adapt to climate change, but this example shows that many of these adaptations are extremely expensive.

Some adaptation can only be pursued by entire communities. For example, Houston and New York are both considering building ocean barriers to protect them from the combination of increasingly destructive storms and sea-level rise. These cost tens of billions of dollars each, so when you add up all of the cities around the world that are within a few feet of sea level, the costs of protecting them will be astronomical.

Ultimately, we all pay for these climate impacts. In some cases, we pay explicitly when we suffer a climate impact (e.g., our house floods) and we have to pay to fix it. Or we pay with tax dollars when our city has to build new infrastructure. Finally, we pay indirectly when money that could have gone into more productive avenues of consumption have to be spent repairing infrastructure that was destroyed by climate change. In this way, we are already paying a climate tax, and it's going to get worse.

Is there a cheaper option? Not really. If we do not spend money on adaptation, then we have to spend money fixing climate damage. If we choose *not* to build coastal defenses for Houston and New York, thereby letting those cities repeatedly flood, we will end up having to pay to fix the damages after every storm, which would also be incredibly expensive.

I will have much more to say about adaptation in Chapter 11, but the bottom line is that there are no low-cost options to effectively deal with the impacts of climate change. As discussed later in this chapter, we are already seeing expensive impacts of climate change with only 1°C of warming. And the future is much grimmer: The Earth may experience several times this warming during this century if we do nothing to address climate change (Figure 8.4). Given the non-linear aspects of climate impacts, it is difficult for us today to imagine the economic and social devastation that would accompany several degrees Celsius of warming this century. But many of readers of this book, perhaps you, will not have to imagine it because they will live through it.

9.3.3 Unmanaged Systems

In the last section, we discussed adaptation for systems that are primarily managed by humans, like cities. But many of the impacts of climate change will be on unmanaged systems, and these will be much harder to deal with. Ocean acidification is an example of an unmanageable impact. About a billion people rely on the ocean as their primary source of protein. If the amount of protein available for human consumption from the ocean decreases because of changes in ocean chemistry, there are no simple adaptations to solve that problem – the protein will have to be made up elsewhere or people will starve.

Many unmanaged ecosystems and their constituents will be affected by climate change. At the individual species level, for example, research shows that warming temperatures are currently driving lizards to extinction. During spring, when energy demands are highest because lizards are reproducing, the warming temperatures reduce the amount of time that lizards can forage for food (if the temperatures get too high, cold-blooded lizards have to rest). If temperatures continue to increase (which we expect), then at some point the time available to forage diminishes to the point where lizards simply cannot find enough food – and extinction ensues. This is already happening, and extrapolating into the future, global warming may lead to the extinction of 40 percent of all global lizard populations by 2080. Note that it is not the global average temperature that matters to lizards, nor even the local average temperature, but the local daily temperatures during one particular time of the year. This emphasizes that it is the details of climate change that ultimately matter, not the broad-brush changes in global average quantities.

Now you may not care much about lizards, but you should care about their extinction for two reasons. First, the environment is a tightly coupled system. There are many examples in history in which humans have intentionally removed a species from the environment because they thought it was harming them (e.g., getting rid of birds because the birds were eating crops) only to find out that that change led to more problems than it solved (e.g., the birds were also eating insects, and with the birds gone the insects proliferated and destroyed much more of the crops than the birds were eating). Today's modern world obscures many of these relationships, but they nonetheless still exist. Removing lizards from an ecosystem may have important effects on the rest of the environment that we do care about, just like pulling a single thread on a sweater can unravel the entire thing.

Second, this is not just about lizards. As warming temperatures drive lizards to extinction, the same warming temperatures will be having deleterious effects on many other species. In fact, a significant fraction of plant and animal species may be at increased risk of extinction if global average temperatures increase by a few degrees Celsius. Thus, at the expense of a mangled metaphor, lizards may be the canary in the coalmine.

Changes to individual species will project onto changes in entire ecosystems, such as alpine meadows or temperate forests. As the climate changes, each component species of an ecosystem will be affected in its own way. Some species may adapt readily, whereas others may be unable to adapt fast enough to survive. Species will also be subject to human interventions and constraints such as land-use change, barriers, and intentional or inadvertent transport.

The aggregate result will be that ecosystems will evolve, with new relationships among incumbents and new arrivals developing in each location. In some cases, the new assemblages may be similar enough to the present ecosystems that we can think of them as basically unchanged. In other cases, however, the new systems may be unlike any present ecosystems, with new species and relationships between them and other ecological surprises. Some ecosystem types are likely to be lost entirely, such as alpine systems, coastal mangrove systems, and coral reefs.

Aside 9.3: What are *ecosystem services*?

Natural ecosystems provide enormous benefits to human society. The mangrove forests that grow in shallow salt-water coastal regions are good examples. They provide important protection for coastal areas from erosion, storm surge (especially during hurricanes), and tsunamis. Their loss will cost us money – either we will have to build expensive coastal defenses to replace the natural defense provided by the mangrove, or we will have to absorb the cost of increased damages. This value, provided to humans for free, is what we mean when we talk about ecosystem services.

Another good example is pollination by bees. Many crops (e.g., apples, almonds, blueberries) are directly dependent on bee pollination as part of their growing cycle. The value of the pollination (by wild bees, at least) is provided free of charge by nature to us. In China, a decline of wild bees has forced farmers to hire people to go from flower to flower and hand-pollinate the flowers using tiny brushes. Thus, ecosystems provide important economic benefits to our society; the impacts on them from climate change will impose potentially steep costs on society.

A particularly important factor in determining the severity of the impacts on natural ecosystems will be the rate of climate change. Ecosystems have adapted to large climate change in the past, such as the warming from the previous ice age. However, the warming predicted for the next century will be many times faster than the average rate of warming since the last glacial maximum 20,000 years ago. As the rate of warming goes up, the ability of the environment to gracefully adapt to the changes declines.

9.3.4 Impacts That Are Already Occurring

Please do not think of climate change as a future problem – as discussed earlier in the chapter, it is already happening and imposing steep costs on us. Flooding from Hurricane Harvey in 2017, for example, cost communities on the US Gulf Coast about \$125 billion in damages. It is incorrect to blame the storm on climate change, of course, but peer-reviewed analyses suggest that climate change increased the amount of rainfall from the storm by about 15 percent. And, since we know that damages are non-linear, meaning that each inch of rainfall does more damage than the previous inch (Figure 9.4b), the fact that climate change increased rainfall by 15 percent leads us to conclude that climate change was responsible for much more than 15 percent of the damage. This corresponds to tens of billions of dollars of damage.

The 2018 California fire season cost \$148.5 billion. Given that California's GDP is about \$3 trillion, this means that those fires cost about 5 percent of GDP. As with Harvey, we cannot say climate change caused the fires. But it is making these fires worse. It has been estimated that climate change doubled the area of fires in California since 1984. Given the non-linearities in climate impacts, we can confidently conclude that climate was responsible for a substantial fraction of the costs of these fires.

Cities on the coast are already spending money to prepare for sea-level rise and more destructive hurricanes. Miami Beach is spending \$500 million to elevate streets and install pumps to ameliorate the impacts of more water. The city of Venice spent \$6.2 billion over the last few decades to build barriers against high water events (known as “acqua alta”) exacerbated by sea-level rise. These huge sums were spent by just two cities – with a combined population of about 300,000 people.

Hotter temperatures are also exacting a terrible toll. Heat-related deaths have been rising, reaching about 300,000 in 2018. Extreme heat also reduces economic productivity for people who work outside, such as agricultural workers. In 2019, over 300 billion hours of work were lost to extreme temperatures.

Overall, we find that climate changes that are already occurring are imposing costs on us. Owing to the non-linear nature of climate impacts, we can expect the costs of the future warming to dwarf the costs we are currently paying.

9.4 Abrupt Climate Changes

Many of the changes I just described – changes in temperature, precipitation patterns, sea level, and so on – are steady changes in the climate system. For example, we expect the climate to warm steadily, by a few tenths of a degree Celsius per decade (as suggested by plots such as Figure 8.5), and we expect sea level to rise steadily, by centimeters per decade. These changes, while incredibly fast geologically, are gradual on human time scales.

An *abrupt climate change* is a sudden and significant shift in some aspect of the climate on human time scales due to human forcing of the climate. As an analogy, imagine that you are sitting in a canoe and you start to lean over. At first, the canoe tilts with you – until, that is, you pass a critical threshold and the canoe suddenly flips over, throwing you and everything else in the canoe into the river. That is an abrupt change, also sometimes referred to as a tipping point.

The worry is that the climate will not actually warm smoothly as greenhouse gases are added to it. Rather, we will add enough greenhouse gas that the climate system will undergo a large and rapid shift to an entirely new state – equivalent to the canoe rapidly transitioning from right side up to upside down. For the change to be considered “abrupt,” it must occur on time scales of decades, comparable to a human life.

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 suddenly plunged (at least in the mid- and high latitudes of the northern hemisphere). The period of low temperatures during the millennium that followed, today known as the Younger Dryas, is thought to have been due to a massive release of water into the North Atlantic from melting glaciers. This freshwater influx disrupted the ocean currents, in particular the Gulf Stream. Because the Gulf Stream transports heat from the tropics to the high latitudes, the shutdown of the Gulf Stream caused mid- and high-latitude temperatures to plummet (this was the basic scientific premise behind the movie *The Day After Tomorrow*).

Thus, abrupt changes do happen, and we must take their possibility seriously. Research on potential abrupt changes has revealed a number of places in our climate system where they could occur. These include:

- Another shutdown of the Gulf Stream, similar to what occurred during the Younger Dryas, leading to rapid, widespread changes in climate;
- A rapid disintegration of the West Antarctic or Greenland ice sheets, which could raise sea level by several meters in a very short period of time;
- Rapid dieback of the Amazon, which would be an ecological catastrophe as well as bringing significant socioeconomic damage to the region;
- 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 (we discussed this in Chapter 6 when we talked about a carbon-cycle feedback);
- A shift in the timing and magnitude of the Indian monsoon, changing seasonal rainfall that billions of people rely on.

However, beyond acknowledging the possibility, there is little the scientific community can say. Climate models do not predict the occurrence of an abrupt climate change, and most experts view the probability to be low over the coming century, although not zero. If an abrupt change did occur, though, it would be a catastrophe. Such low-risk, high-consequence events pose significant challenges to our society. The tendency is to ignore the risk until it occurs, which is why dams are built after floods, and not before. However, for these types of events, once the abrupt change takes place, it will be very difficult, if not impossible, to gracefully manage the impacts. This makes the strategy of ignoring the risk a precarious proposition.

9.5 Putting It Together

I could write an entire book on how climate change will impact human society. But this chapter is long enough, so let me try to pull things together here. We know the climate is changing, and this is making extreme events more severe. These events are imposing costs on us *today*. We are, in other words, already paying a climate tax.

And this is occurring with only 1°C of warming. Warming over the twenty-first century may be several times this, comparable to the warming since the end of the last ice age. Given that we are adapted to our present climate, it is terrifying to think about what the climate impacts would be with, say, 4°C of warming.

So when people tell you that solving climate change will cost us money and hurt the economy, you should understand that *not* solving climate change is already costing us money and hurting the economy. In considering action on climate, you have to balance the costs of action with the costs of inaction. This something we will also discuss in later chapters.

You might be tempted to look at climate change as just another problem and say, “Well, we’ll deal with it.” That’s true, of course. Humans will deal with the problems that climate

change creates, and we'll emerge at the other end. So the real question is how well we deal with it and in what shape we'll emerge.

As I write this in late 2020, the United States is still gripped by the coronavirus pandemic, with 200,000 new cases and 2,500 deaths each day. The Trump Administration's response, if you can call it that, has been one of profound incompetence, which has led to unnecessary deaths, unnecessary economic loss, and unnecessary suffering. It didn't have to be like that. Other countries have not been suffering the way the United States is, and those countries will emerge from the pandemic in much better shape.

The lesson here is that humans control, to a large extent, how we are impacted by natural disasters. If we handle the climate change the same way the United States handled the coronavirus pandemic, then we will suffer mightily. Or we can adopt smart policies that actually address the problem, as many other countries did during the pandemic. This will determine how bad climate change will be for you, your kids, and your grandkids.

With that as motivation, the book will now turn its attention to our various policy options. Make no mistake, the stakes are very high.

9.6 Chapter Summary

- The amount of warming predicted for the twenty-first century (a few degrees Celsius) is similar to the warming since the last ice age (6°C). This means that the warming over the next century or two may herald a literal remaking of the Earth's environment and our place within it.
- We are adapted to our present climate, so any significant change (in any direction) is likely to be detrimental.
- There are a number of virtually certain impacts of climate change: The climate will get warmer (with more extreme heat events), precipitation patterns will change, sea level will rise, some storms (i.e., hurricanes) will get more destructive, and the oceans will become more acidic. These are serious impacts that should compel our attention.
- The science tells us that we already see extreme weather events becoming more extreme because of climate change, with negative impacts on humans.
- Large impacts can appear suddenly in response to small changes in the climate system, which we describe as non-linearity. This arises because of thresholds in the climate system. As long as the climate system stays below the threshold, damages are small, but if the system exceeds a threshold, even by a small amount, then damages can be large.
- Natural ecosystems may also be severely disrupted. These natural systems provide services of great value to humans, so their disruption could provide significant challenges to us.
- Abrupt changes are low-probability, high-consequence events. An example of an abrupt change was the reorganization of the ocean's circulation during the Younger Dryas period about 12,000 years ago. Although scientists do not expect them to occur this century, they cannot be ruled out.

See www.andrewdessler.com/chapter9 for additional resources for this chapter.

TERMS

Abrupt climate changes
Ecosystem services
Extreme-event attribution
Global climate model (GCM)
Parameterizations
Storm surge

PROBLEMS

1. Your third cousin once removed asks you why we will not be better off in a warmer climate. What do you tell him?
2. Your friend says, “Climate scientists are such alarmists. First they say that floods will become more frequent, and then they say that droughts will become more frequent. Come on, which one is it? They cannot both occur!” What do you tell him?
3. As discussed in this chapter, temperatures are not expected to rise uniformly across the globe. You may need to review Chapters 3 and 4 to answer these questions.
 - (a) Why is there more warming at high latitudes than the tropics?
 - (b) Why will land warm more than the ocean?
 - (c) Why do temperature contrasts (e.g., night versus day) decrease in a warmer climate?
4. Precipitation
 - (a) How is precipitation expected to change in a future climate?
 - (b) Why do changes in the form of precipitation (rain versus snow) matter?
5. Explain a few ways that climate change impacts the following. You may need to do some research outside of the book to produce a complete answer.
 - (a) Public health
 - (b) National security
 - (c) Food availability
 - (d) Water availability
6. Why will it be easier for the United States and Western Europe to deal with climate change than countries in Africa?
7. (a) What do scientists mean when they talk about “abrupt climate change?”
(b) Give an example of an abrupt climate change that has occurred in the past.

10 Exponential Growth

When a danger is growing exponentially, everything looks fine until it doesn't
— *Washington Post*, March 10, 2020¹

Before we continue our discussion of climate policy, we need to take a detour to examine exponential growth, which may be the most important concept that you have never heard of. It touches many aspects of your life, from the growth of credit card debt and pandemics to governing key processes in biology, physics, economics, and, yes, climate change policy.

10.1 What Is Exponential Growth?

First, a definition: *exponential growth* means that the rate of growth is directly proportional to the present size. A good example of exponential growth is the accumulation of money in a savings account. Imagine that you deposit \$100 into a bank account with an *interest rate* of 10 percent per year.² After the first year, you receive interest equal to 10 percent of the balance of \$100, which is \$10. This interest raises the balance of the account to \$110. After a second year, the interest is 10 percent of the balance of \$110, which is \$11. This increases the balance to \$121. Table 10.1 shows the growth of the bank account over 101 years.

This growth is exponential because the increase in the bank balance during any year is proportional to the bank balance in that year. In fact, anything growing at “ r percent per year” is growing exponentially. The key parameter in exponential growth is the rate of growth, or r . For bank balances, credit cards, or mortgages, r is usually called the interest rate, whereas in other contexts r may have other names (later in the chapter, I will refer to r as the discount rate).

Usually, r is expressed in percent per year. Given a growth rate of r percent per year, a quantity grows by a factor of $1 + r/100$ each year. For an initial value P , the quantity grows to $P(1 + r/100)$ after 1 year. For a bank balance of \$100 and an interest rate of 10 percent per year, the bank balance after 1 year is $\$100(1 + 10/100) = \$100(1.1) = \$110$, the same answer we obtained earlier.

¹ www.washingtonpost.com/opinions/2020/03/10/coronavirus-what-matters-isnt-what-you-can-see-what-you-cant/, accessed May 5, 2020.

² We are assuming here that the interest is compounded annually. Most bank accounts and credit cards calculate interest monthly, meaning that the balance is increased each month by the balance times the annual interest rate divided by 12. Monthly compounding grows the balance a bit faster for a given interest rate than annual compounding.

Table 10.1 Calculation of the balance of a bank account with an initial investment of \$100 at an interest rate of 10 percent per year

Year	Interest (\$)	Balance (\$)
Initial balance		100
After 1 year	10	110
After 2 years	11	121
After 3 years	12.10	133
After 4 years	13.30	146
After 5 years	14.60	161
After 6 years	16.10	177
After 7 years	17.70	195
After 8 years	19.50	214
⋮		
After 100 years	125,278	1.38 million
After 101 years	137,806	1.52 million

At the end of 2 years, the balance is $P(1 + r/100)(1 + r/100)$. This is simply the balance at the end of the first year, $P(1 + r/100)$, multiplied by another factor of $1 + r/100$ to account for growth during the second year. Thus, the bank balance at the end of the second year is $\$100(1 + 10/100)(1 + 10/100) = \$100(1.1)(1.1) = \$110(1.1)^2 = \121 .

You may see a pattern here. After n years, an initial investment of P will grow to a final value F :

$$F = P(1 + r/100)^n \quad (10.1)$$

This is the formula I used to generate the values in Table 10.1.

10.2 The Rule of 72

When thinking about exponential growth, it is frequently useful to consider the *doubling time* – the length of time that it takes for something growing exponentially to double. From Table 10.1, for example, we see that \$100 invested at 10 percent per year will double after about 7 years. After another 7 years, the \$200 doubles to \$400, and after another 7 years, the \$400 will grow to \$800.

A simple way to estimate the doubling time is to use the *rule of 72*: The doubling time is 72 divided by the growth rate. Using this equation, we see that the doubling time at 10 percent per year is $72/10 = 7.2$ years — this is consistent with Table 10.1, which shows that the initial balance doubles sometime between the end of year 7 and the end of year 8. Note that doubling time is a function only of growth rate. Thus, for a growth rate of r , the doubling time is the same regardless of the size of the growing quantity.

Table 10.2 The balance of \$100 invested in year 2000 at an interest rate of 7.2 percent per year, using rule of 72 and Equation 10.2

Year	No. of doublings	Value (\$)
2000	—	100
2010	1	200
2020	2	400
2030	3	800
2040	4	1,600
2050	5	3,200
2060	6	6,400
2070	7	12,800
2080	8	25,600
2090	9	51,200
2100	10	102,400

Using this rule, you can frequently do exponential growth problems with pencil and paper – or even in your head. For example, let us put \$100 in the bank at 7.2 percent interest in year 2000. What is the balance in year 2100? The doubling time is $72/7.2 = 10$ years, so that the balance doubles every 10 years.

In equation form, after n doublings, an initial investment of P grows to a final value F :

$$F = P(2^n) \quad (10.2)$$

Table 10.2 shows the balance at the end of every decade, calculated using this equation. After 100 years and 10 doublings, the \$100 investment has grown to $\$100 \times 2^{10} = \$102,400$ – illustrating the power of exponential growth.

We could also have used Equation 10.1 to calculate the balance in 2100: $F = \$100(1 + 7.2/100)^{100} = \$104,587$. This is very close to the value calculated for 2100 by use of the doubling time, although the estimates differ slightly because the rule of 72 is an approximation, so calculations using it are almost always slightly off.

As another example, imagine investing \$100 at an interest rate of 14.4 percent. How long would you have to leave this investment in the bank to yield \$1 trillion ($\10^{12})? First, let us figure out how many doubling times it would take. Using Equation 10.2, we can write the relevant equation as

$$\$100(2^n) = \$10^{12} \quad (10.3)$$

Solving this equation³, we find that $n = 33.2$. In other words, an initial investment of \$100, doubled 33.2 times, yields \$1 trillion. Now let us calculate how many years that takes. At an

³ There are several ways to solve this equation. One way is to solve the equation algebraically by taking the log of both sides of the equation and rearranging to solve for n (see www.andrewdessler.com/exponent-solution). You could also

interest rate of 14.4 percent per year, the doubling time is $72/14.4 = 5$ years, so 33.2 doublings take 166 years.⁴

Most of the accumulation occurs in the last few doubling periods. In fact, \$500 billion dollars, half of the total, is earned in just the last doubling period, and 97 percent of the \$1 trillion is earned in the last five doubling periods. And, had the investment period been cut in half (from 166 to 83 years), you would have \$10 million at the end, 1/10,000 of what you earn for the entire time period. Thus, exponential growth is heavily weighted toward the end of the investment period. This has some important consequences, which we investigate in the next section.

10.3 Catastrophe Is Closer Than You Think

10.3.1 Lily Pads

The human brain is not wired to understand exponential growth the way we intuitively understand linear growth. As an example, consider the following scenario: there is a lake on which someone places some lily pads. The lily pads double in size each year, eventually covering the entire lake after 40 years.

How long does it take the lily pads to cover *half* the lake? To get the answer, all you have to do is remember that the lily pads double in size every year, so if it takes 40 years for them to cover the entire lake, then they covered half the lake 1 year earlier. Thus, the correct answer is 39 years. The trajectory of growth of lily pads is shown in the blue line in Figure 10.1.

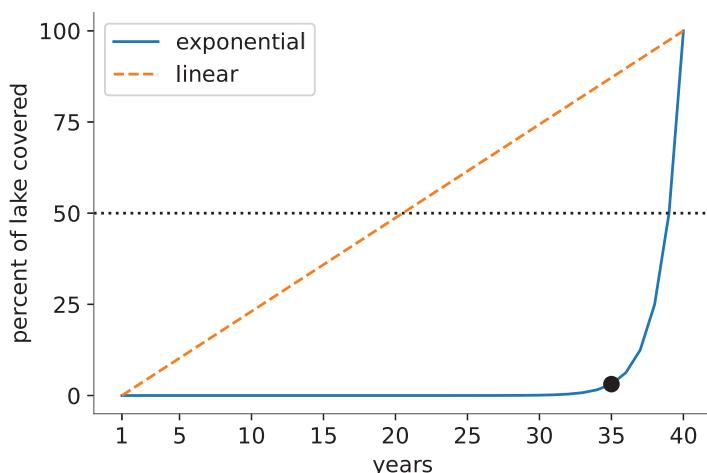


Figure 10.1 Fraction of the lake covered by lily pads. The blue line shows exponential growth, while the orange dashed line shows linear growth. The black dot shows that 3 percent of the lake is covered after 35 years.

solve it iteratively, meaning that you guess a value for n and plug it into your calculator. If that n produces too large a number, then reduce your estimate of n and repeat the process; if it produces too small a number, then do the opposite. With a bit of practice, you can quickly converge on the correct answer with five to ten guesses.

⁴ The exact answer derived using Equation 10.1 is 171 years.

A lot of people don't get the right answer, though, because they reason this way: If it takes 40 years to cover the entire lake, then it will take 20 years to cover half the lake. What they are doing here is implicitly drawing a straight line between zero percent coverage in year 1 and 100 percent in year 40 (that's the orange line in Figure 10.1). This is "linear thinking," in which the increase in each year is a fixed amount. Such thinking comes naturally to the human mind.

Exponential growth, on the other hand, is much harder for humans to imagine. Because the growth in any year is proportional to the amount in that year, the growth is strongly end-loaded, with most of the growth occurring in the last few doubling periods. The non-intuitive nature of exponential growth means that people often underestimate risks that are growing exponentially. To see this, let's imagine that, in year 35, you go to the local government and show them the data up to year 35 (the dot in Figure 10.1) and tell them that we have a lily pad problem – the lake is going to be covered soon.

It is likely that local government officials will look at the data and tell you that you're crazy. After 35 years of growth, lily pads are only covering about 3 percent of the lake. If they mistakenly apply linear thinking to this, they'll conclude that it will take a thousand years before lily pads cover the entire lake. So the local government officials tell you to take your alarmist garbage and go away.

Of course, in just a few years they'll realize that you were right, and they will begin to take action. Imagine that, in year 39, when the lake is half covered, they remove enough lily pads to reduce the coverage to 25 percent through huge and expensive remediation efforts. How much time does that buy? After 1 year, the lily pad coverage is back up to 50 percent, so the herculean removal effort only bought them 1 year of delay.

The lesson here, shown more clearly in the next section, is that you need to address exponentially growing threats early, usually before the risk is clearly apparent. By the time the risk is obvious, it's too late.

10.3.2 Coronavirus

As I write this in 2020, I am stuck at home as part of the response to the coronavirus pandemic. I'm not complaining – I avoided getting sick. This episode has also given me one of the best examples of exponential growth that any textbook author could possibly imagine.

To understand why very contagious diseases grow exponentially, imagine that one person is infected on day 1. This "patient zero" infects one other person, so two people are infected on day 2. These two people each infect one additional person, so four people are infected on day 3. Each of the infected continues infecting one additional person each day – so on day 4 there are eight infected people, and on day 5 there are 16 infected. In other words, the growth is proportional to how many infected people there are. This is the very definition of exponential growth.

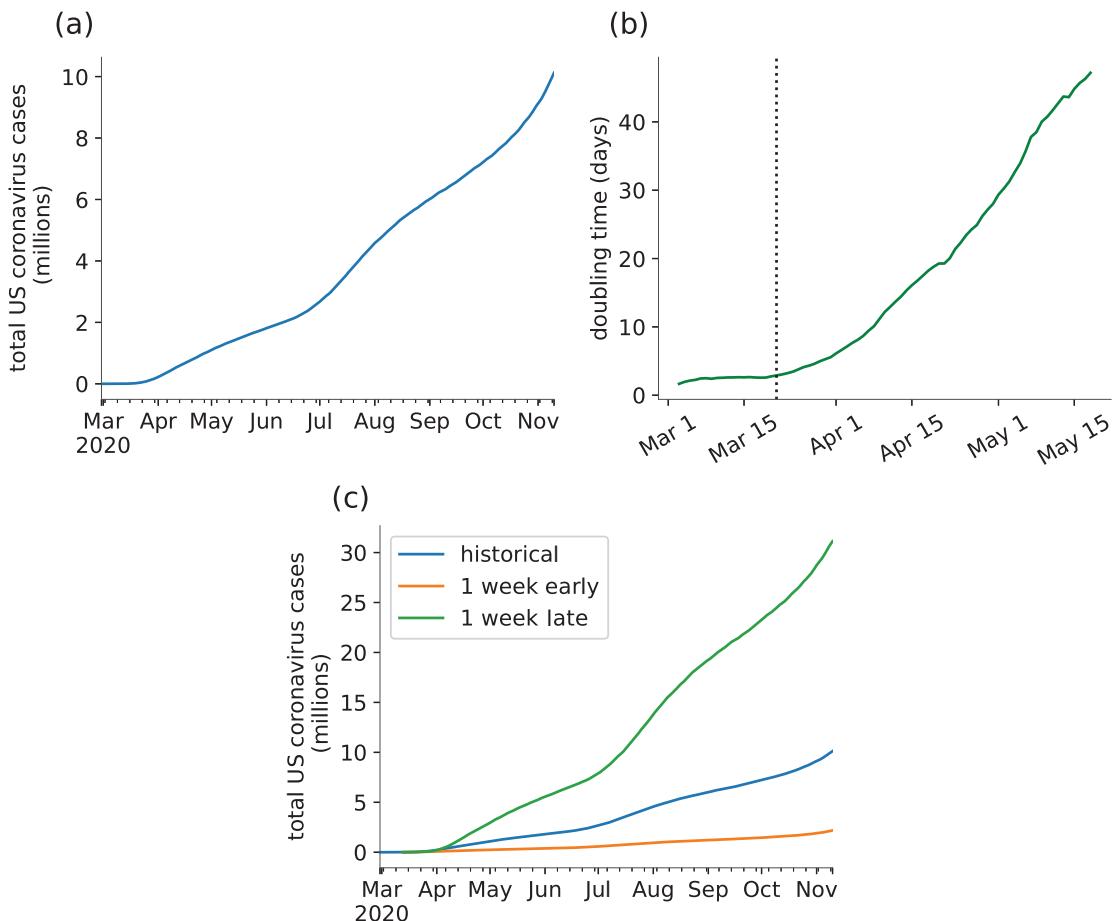


Figure 10.2 (a) Number of reported cases of coronavirus in the United States between March and November, 2020. (b) The time series of doubling time derived from the day-to-day increase in the number of cases between March and May 2020. The dotted line on March 21 is the approximate time that lockdown began in the United States. (c) Estimates of how many cases there would have been if the United States had instituted a lockdown one week earlier (orange line) or one week later (green line). The blue line is the actual observed number of cases, the same line that's plotted in panel (a). Estimates of the number of cases with earlier or later lockdown come from shifting the doubling values after March 20 forward or backward in time by one week and using that to reconstruct the total number of cases. When shifting the doubling time series forward, a value of 40 days is used to pad the time series; when shifting backward, a value of 5 days is used to fill the middle part of the time series. Data were obtained from <https://github.com/COVID19Tracking/website>, accessed November 12, 2020.

As I said in the last section, most people don't understand exponential growth, and so they are not worried about this disease at this point. After all, you're 5 days into the infection and only 16 people are infected, an average of just a few infections per day. Obviously, you think, this disease is not a big deal. If you felt that way, you wouldn't

be alone. For example, President Donald Trump said on February 26, 2020, “When you have 15 people, and the 15 within a couple of days is going to be down to close to zero, that’s a pretty good job we’ve done.”⁵

Those playing down the risk did not appreciate the power of exponential growth. While there may have only been 15 cases in the United States on February 26, there were thousands of cases by mid-March and, by early November, there were *10 million cases* (Figure 10.2a). To better quantify the spread of the disease, we show in Figure 10.2b the doubling time implied by the day-to-day increase in the number of cases for the first 3 months of the pandemic in the United States. In the 14 days between March 1 and March 15, the number of cases in the United States rose from 40 to 4,800 – an increase of a factor of 120, about seven doublings. This means that the number of cases were doubling about *every 2 days*.

In mid-March, just 3 weeks after Trump said coronavirus was nothing to worry about, governors of US states began ordering lockdowns, indicated by the dotted line in Figure 10.2b. This had a noticeable impact on the growth rate. As people stayed home, wore masks, and social distanced, transmission of the disease slowed and the doubling time began rising rapidly.

Given the rapidity of exponential growth, small changes early in the event can have a huge impact later. Had our leaders issued lockdown orders just *one week* earlier, the impact would have been dramatic (Figure 10.2c) – in mid-November, there would have been only 2 million cases, an 80 percent reduction in the number of cases. On the other hand, had they delayed the lockdown order by *one week*, there would have been 30 million cases in mid-November, a factor of 3 larger than reality.

We can learn a lot from the coronavirus. First, the infectious disease experts *knew* what was going to happen well in advance, but they were ignored and overruled by policy-makers. Ditto for climate change – the experts are warning us, but our elected leaders are pretending that they can ignore the problem without consequence. It didn’t work for coronavirus and won’t work for climate. We know how to deal with coronavirus – just look at how other countries successfully managed the pandemic – but the United States simply chose not to. We also know how to deal with climate change and are similarly choosing not to deal with it.

Finally, the best and easiest time to deal with coronavirus was *before* it became a pandemic – in early 2020, when the number of cases was measured in dozens. Similarly, the best and easiest time to deal with climate change is before significant changes to the climate. We may have already missed that point in time, in which case the second-best time to deal with climate change is now. Like the coronavirus, delay in responding to climate change simply locks in more and bigger impacts. We’ll discuss many of these issues in later chapters.

⁵ Quoted in www.npr.org/2020/04/21/837348551/timeline-what-trump-has-said-and-done-about-the-coronavirus, accessed May 7, 2020.

10.3.3 Malthus

Probably the best-known warning of the dangers of exponential growth came about 200 years ago from *Thomas Malthus*. Malthus was an English cleric and scholar who argued that population grows exponentially whereas food production grows in a linear fashion. Linear growth means that the increase in each year is a fixed amount: Food production after n years is $F(n) = an + b$, where a and b are constants and n is the number of years. This is quite different from exponential growth, in which the increase is a fixed fraction of the growing quantity. Mathematically, it is easy to show that exponential growth will always outpace linear growth, and this led Malthus to conclude that an exponentially increasing population would eventually outstrip the world's ability to feed those people, resulting in widespread starvation – what we now call a Malthusian catastrophe.

Malthus was correct that population grows exponentially. However, in the two centuries since his prediction, technological developments (e.g., development of fertilizers and pesticides) have allowed food production to increase exponentially along with population. As a result, we have not experienced this Malthusian catastrophe. We are not, however, out of the woods yet. Exponential growth cannot continue indefinitely: Both food production and population will eventually cease to grow exponentially. The question is which one plateaus first. If exponential food production growth stops before exponential population growth does, then Malthus' prediction may yet come true. If, however, population growth ceases before food production growth, then Malthus may be forever wrong. Time will tell.

As we discussed in Chapter 9, societal problems often occur when some important quantity passes a threshold. For example, increases in rainfall intensity don't cause problems until the rain rate exceeds the ability of the system to take rainwater away. Once that happens, large damages occur (Figure 9.4). For the coronavirus, important thresholds include the number of cases requiring hospitalization exceeding the number of hospital beds or the available lifesaving equipment (e.g., ventilators). For Malthus, the key threshold occurs when population exceeds the amount of food that can be produced. If that were to happen, starvation would be the result.

As these examples show, because exponential growth is so fast, a system can go from well below the key threshold to above it much faster than intuition would suggest. In other words, *when things are growing exponentially, you are a lot closer to catastrophe than you realize*.

10.4 Discounting

In this section, I describe the financial concept of discounting, which plays a key role in understanding and evaluating policy options for dealing with climate change.

10.4.1 The Time Value of Money

In the business world, people often know of costs or benefits that will occur years in advance. As an example, suppose you take out a loan for \$25,000 that must be repaid in 15 years. How much would you be willing to pay *today* to eliminate that future expense? One way to answer this is to determine how much you would have to invest today in order to have \$25,000 in 15 years. We can get the answer by rearranging Equation 10.1:

$$P = F/(1 + r/100)^n \quad (10.4)$$

Here F is the future expense, which will be incurred in n years, r is the interest rate in percent, and P is the amount you need to invest today. Given an interest rate of 5 percent, we need to invest about \$12,000 today in order to have \$25,000 in 15 years. In other words, we can view \$12,000 today as being equal to \$25,000 in 15 years. We refer to the value today of a future expense or benefit as the *present value* – i.e., \$12,000 is the present value of \$25,000 in 15 years. The process of calculating the present value is referred to as *discounting*.

One important conclusion you can draw from this is that *money today is worth more to you than money in the future*. The parameter r in Equation 10.4, frequently referred to as the *discount rate*, quantifies the rate at which money loses value as it recedes into the future – each year, money loses r percent of its value. This is why, for example, interest is charged on loans: if I loan you \$100 today, you have to pay me back *more* than \$100 at some point in the future in order to fairly compensate me for the loan.

Example 10.1: What would you do?

You can use discounting to help make financial decisions. Imagine you walk into an electronics store, searching for a new television. You select one and are informed that you have two payment options: You can pay \$1,000 right now or get it “with no money down” and pay \$1,100 in 1 year. Which option do you choose? You wish to pay the least amount for the TV, but because your options are payments at different times, you need to use discounting to determine which of the two options is cheapest.

The present value of \$1,000 paid today is simply \$1,000 – this is no discounting. The present value of \$1,100 in 1 year is $\$1,100/(1 + r/100)$, where r is the discount rate. If you choose a discount rate of, say, 5 percent, then the present value is \$1,047. This is more than \$1,000, meaning that \$1,100 in 1 year has a higher value to you than \$1,000 today. Because you want to pay as little as possible for the television, you therefore choose the option with the lower present value and pay \$1,000 today for your TV.

For a discount rate of 15 percent, on the other hand, the present value of \$1,100 in 1 year is \$956, so in that case \$1,000 today is more expensive than \$1,100 in a year’s time – and you would therefore prefer to pay \$1,100 in 1 year. If you choose a discount rate equal to 10 percent, then the present values are equal, and you would have no preference about paying \$1,000 today or \$1,100 in 1 year. This example shows how the choice of discount rate can make a profound difference in the answer you get.

The utility of discounting is that it allows comparison of costs and benefits occurring at different times. In the policy debate over climate change, our choice is between spending money today to reduce emissions of greenhouse gases, thereby reducing the impacts of climate change in the future, or doing nothing now and spending money dealing with the impacts of climate change throughout the twenty-first century and beyond.

As a simplified example, imagine our choice is between spending \$100 billion today or \$1 trillion in 100 years. Discounting allows us to quantitatively compare these two options. If we assume a discount rate of 3 percent, then the present value of \$1 trillion in 100 years is $10^{12}/(1.03^{100}) = \$52$ billion. This is less than the alternative of spending \$100 billion today, so (from a purely financial perspective) we would prefer to pay \$1 trillion in 100 years than \$100 billion today. This type of analysis, in which you compare the present value of the costs and benefits of various options, is known as a cost–benefit analysis, and economists frequently use it to provide guidance to policymakers about alternative policy options.

10.4.2 The Discount Rate

In both the television purchase and climate examples just given, the answer we get is dependent on the discount rate. In the climate example, a discount rate of 3 percent yields the conclusion that we would prefer to do nothing now and pay later to address the impacts of climate change. However, if the discount rate were 2 percent, then the present value of \$1 trillion in 100 years is \$138 billion, and we would rather pay \$100 billion today to reduce emissions.

So how do we determine the correct discount rate? The discount rate really is a combination of two different judgments. First is what is known as *time discounting*, which is the preference to consume now rather than later. If offered \$100 now or \$100 in a week, just about everyone would choose to get the money now. After all, why would you wait? Experiments show that animals also exhibit this behavior. I know that if I give my dogs the choice of having dinner now or in an hour, they tell me in no uncertain terms that they want to eat now. In other words, most people (and dogs) have a positive time discount rate: Goods and services now are worth more than the same goods and services in the future.

The climate problem covers periods longer than a human lifetime. In that case, the time discount does not represent our preference for us to consume now rather than later. Rather, it represents our preference for us to consume rather than future generations. Given that consumption can be roughly equated to welfare, the time discount rate then expresses how much we value our welfare above the welfare of future generations.

From a moral standpoint, most people agree that it is unethical to place a higher value on our own welfare over that of future generations, which implies that the time discount rate should be set to near zero. Nonetheless, it is also clear from our society’s actions, such as our low rate of savings and our failure to address big problems facing future generations (e.g., climate change), that we do value our own generation more highly, which implies a positive time discount rate.

The other part of the discount rate is known as *growth discounting*, and it reflects the fact that a dollar means more to poor people than it does to rich people. For example, if a billionaire walking down the hall sees a \$1 bill on the floor, would he stop to pick it up? Probably not – if you have a billion dollars, another dollar does nothing to improve your welfare. If you are very poor, however, you are most certainly going to stop and pick up the \$1 bill – it might be the difference between having dinner that night or not.

In economics jargon, the utility of \$1 to the billionaire is much lower than the utility of \$1 to the person living in poverty. In the case of climate change, we expect future generations to be richer than we are, just like we are richer than those living 100 years ago. And because future generations are richer, they will be better able to pay costs associated with climate change than we are. This suggests a preference for our generation to push the costs of addressing climate change onto richer, future generations. This is quantified in the growth discount rate, which is the rate at which the utility of money – how much each dollar means to society – declines with time as the world gets richer.

The discount rate used in present-value calculations is determined by combining the time and growth discount rates. Unfortunately, the choice of both time and growth discount rates is as much a value judgment as an objective fact, and there are wide disagreements about what discount rate to use. Some economists argue the discount rate should be around 1 percent, whereas others argue for higher values such as 4 percent.

This choice makes a huge difference in climate problems. For future impacts of \$1 trillion in 100 years, the different discount rates yield present values of \$379 billion (for a 1 percent discount rate) or \$19 billion (for a 4 percent discount rate). The optimal policy for climate change using different discount rates may therefore be completely different.

10.5 Putting It Together: The Social Cost of Carbon

Imagine that you emit a tonne of carbon dioxide to the atmosphere. As discussed in the first half of the book, this tonne of carbon dioxide will warm the climate over many thousands of years – until the carbon cycle completely removes it from the atmosphere. And as we saw in Chapter 9, this warming imposes costs on our society, such as construction of expensive defenses against the sea (e.g., seawalls), rebuilding of damaged infrastructure, or relocation of communities being inundated.

This means that the costs of climate impacts from this tonne of carbon dioxide are spread over time. As a simplified example, imagine that the tonne causes \$1 of damage every year for 300 years (the blue line in Figure 10.3). Using discounting, we can estimate the value *to us today* of the damages in any year in the future. Assuming a discount rate of 3 percent, the present value of the cost of \$1 of impacts in 1 year is $\$1/1.03$, in 2 years is $\$1/1.03^2$, and in n years is $\$1/1.03^n$. This is plotted as the orange line in Figure 10.3, and it shows that, for example, the value to us today of \$1 of climate damages in 50 years is \$0.23 using a 3 percent discount rate (indicated by the orange dot in the figure).

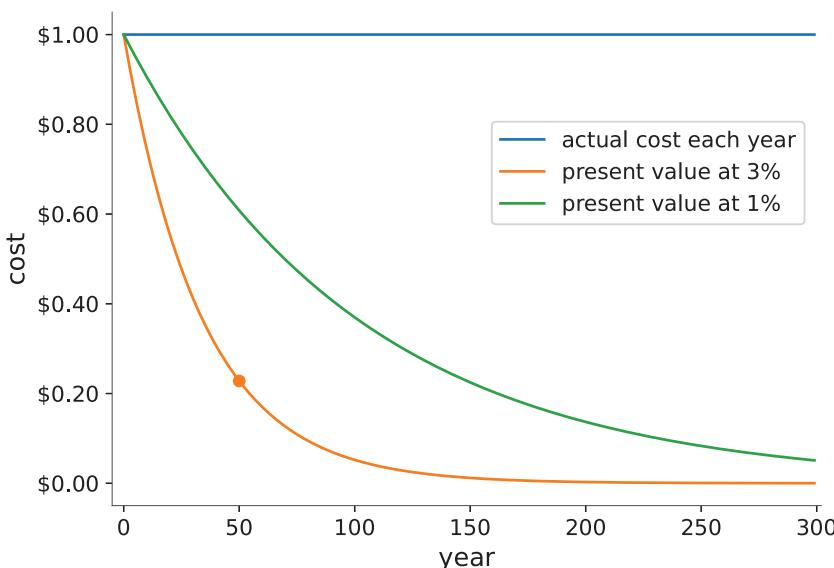


Figure 10.3 The present value of \$1 of climate damages, as a function of the year the damages took place. The blue line is the actual value of the climate damages in each year, while the orange and green lines are the present value of those damages at a 3 and 1 percent discount rate. The orange dot shows that the present value of \$1 of damage in 50 years is \$0.23 when using a 3 percent discount rate.

The figure shows that, as the damages recede into the future, the present value of the damages declines rapidly. For the 3 percent discount rate, costs beyond about 100 years from now have a present value of nearly zero. Figure 10.3 also shows the present value using a 1 percent discount rate. For the 1 percent discount rate, the present value drops off more slowly, and damages in 300 years are making contributions to the present value.

We can calculate the total cost to us today from the emission of this tonne of carbon dioxide by summing the discounted costs for every year. This total cost is frequently referred to as the *social cost of carbon*, and in this simple example it equals \$34 and \$96 for the discount rates of 3 percent and 1 percent, respectively.

The social cost of carbon can be used to evaluate climate change policies. Imagine that a coal-fired power plant will release 1 million tonnes of carbon dioxide to the atmosphere during the coming year, after which it is scheduled to shut down. Now imagine that the local government can pay the utility that owns the power plant \$30 million to shut down the plant now and replace it with wind energy (which produces no carbon dioxide). We can use the social cost of carbon to figure out if this is a good deal. If the social cost of carbon is, say, \$36 per tonne, then the benefit from shutting down the coal plant today is \$36 million. Thus, the benefit is more than the cost, so this tells us that the government should definitely pursue this plan.

10.5.1 The Obama Administration

Expert estimates of this quantity from the Obama administration are listed in Table 10.3. There are several things worth noting in this table. First, seemingly small changes in the discount rate lead to large changes in the social cost of carbon. This emphasizes the central role of the discount rate in the debate on climate change policy.

Table 10.3 Estimates by the Obama Administration of the social cost of carbon per tonne of carbon dioxide (in 2007 dollars) for different discount rates and for different year of emission.

The 5%, 3%, and 2.5% columns are the averages of the estimates from a large number of economic models; the 3%, 95th percentile column is the value exceeded by 5% of the estimates using a discount rate of 3%.

Year	Discount rate			
	5%	3%	2.5%	3%, 95th percentile
2020	\$12	\$42	\$62	\$123
2025	\$14	\$46	\$68	\$138
2030	\$16	\$50	\$73	\$152
2040	\$21	\$60	\$84	\$183
2050	\$26	\$69	\$95	\$212

Source: Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis, Under Executive Order 12866 (<https://obamawhitehouse.archives.gov/sites/default/files/omb/inforeg/scc-tsfd-final-july-2015.pdf>, retrieved May 14, 2020).

Second, the social cost of carbon rises throughout the twenty-first century. The reason for this is that damage from climate change is non-linear: each degree of warming produces more damage than the previous degree. Thus, as we add carbon dioxide to the atmosphere, the cost of the damage from each additional tonne is more than the cost from the previous tonne.

Third, the “3 percent, 95th percentile” column is the value exceeded by 5 percent of the estimates using a 3 percent discount rate. Comparing this to the 3 percent column, which is the average of all estimates using that discount rate, gives some idea of how wide the range of estimates is for a single discount rate. The large difference between these values says that, even at a single discount rate, there is a wide range of estimates of the social cost of carbon.

The wide range arises from the fact that putting a dollar price on the impacts of climate change requires a set of linked predictions, all of which are highly uncertain. We need to predict how the climate will change in individual regions, how the regional climate change will affect people and ecosystems, and how people and ecosystems will in turn adapt to these climate changes. Then, a dollar value must be assigned for the cost of the adaptation as well as the cost of changes that were not adapted to.

For some impacts, a dollar value is easy to assign. For the loss of goods and services sold on the open market (e.g., agricultural products, farmland, and coastal property), the market value can be used as an estimate of the value of their loss. Other impacts are much more difficult to value. A good example is the existence of polar bears. They have little market value, but (to me, at least) they do have social value – I believe that driving them to extinction would represent a loss to humanity. Most people would agree that there is some value in their continued existence, but there might be great disagreement over exactly how

Table 10.4 Estimates from the Trump Administration of the social cost of carbon per tonne of carbon dioxide (in 2016 dollars) for different discount rates and for different year of emission.

Year	7%	3%
2020	\$1	\$6
2025	\$1	\$7
2030	\$1	\$8
2040	\$2	\$9
2050	\$2	\$11

Source: Table 4-1 of Regulatory Impact Analysis for the Proposed Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units; Revisions to Emission Guideline Implementing Regulations; Revisions to New Source Review Program, EPA-452/R-18-006, August 2018 (www.epa.gov/sites/production/files/2018-08/documents/utilities_ria_proposed_ace_2018-08.pdf, retrieved May 14, 2020).

much. If economists simply ignore the value of things like polar bears, then they are implicitly assigning a value of zero to them. If they want to include these costs, on the other hand, they have to come up with some way to estimate a value that is fundamentally subjective and may vary from person to person and analysis to analysis.

The difficulty in calculating the overall costs of climate impacts is responsible for the large spread of estimates in Table 10.3. Despite the large range of estimates, however, there are a few things we can conclude with confidence:

- (1) The social cost of carbon is not zero. Every credible economic analysis of climate change has found that there are costs from the emissions of greenhouse gases and the associated climate change.
- (2) While there is uncertainty in our estimates of the social cost of carbon, very large costs cannot be ruled out. Such large costs are associated with the most dire climate change impacts, and this possibility drives much of the concern about the climate problem.

Despite the uncertainty in this quantity, regulators must nonetheless assign a single value for the social cost of carbon in order to use it in cost–benefit analyses and other regulatory decisions. In 2013, the Obama Administration selected \$36 per tonne of carbon dioxide as the best estimate of the social cost of carbon.

10.5.2 The Trump Administration

The Trump Administration revised the social cost of carbon by making two different assumptions than were made by the Obama Administration: First, they used larger discount rates and, second, they only counted the costs associated with impacts occurring within the United States. Doing that yields estimates of the social cost of carbon as low as \$1 per tonne (Table 10.4).

The argument in favor of using a discount rate of 7 percent is that this is more in-line with the rate of return from private investments. The rationale is that money spent on climate change will compete with private-sector investments, so using this discount rate ensures that climate change policies will generate a rate of return on their investment comparable to the private sector.

The problem with estimating the discount rate this way is that private investments typically cover short time horizons, at most a few decades – businesses simply do not make business decisions that extend for a century or more. The time scale of climate change, however, is intergenerational and covers centuries. On long time scales relevant for climate change, using a discount rate that businesses use for a decade or two produces dubious answers: At a discount rate of 7 percent, you would only pay \$1 billion to head off \$1 trillion of damages in 100 years. Using such a high discount rate effectively guarantees that we will choose to do nothing today about climate change. Which is, of course, the point.

As discussed in Subsection 10.4.2, the choice of a discount rate represents a philosophical view of how our economy and society should value costs and benefits over time. Most environmental economists who study the problem favor using lower discount rates, 1–4 percent, to account for the fact that costs and benefits of climate change occur over very long times (multi-decadal or centennial) that cover many generations of humanity.

Only counting impacts occurring in the United States is also problematic for two reasons. The first is practical: Given that we live in a global economy, climate impacts anywhere affect our economy and well-being. For example, China is an economic power and one of the major trading partners of the United States. If climate change caused economic and political instability there, the economic fallout would certainly affect the United States: Farmers in the Midwest would sell less to China, production in the many US companies that rely on supply lines that go through China would be disrupted, etc. The net impact would be higher prices for some things and collapsing markets for others – and the US economy would be worse off for it.

The second problem with only counting impacts in the United States is moral. It is certain that US emissions contribute to climate impacts everywhere on the Earth. Is it really acceptable for a nation to say, essentially, that they put zero value on harms they are imposing on other countries? To do that is (to me, at least) deeply problematic.

Ultimately, the choices made by any Presidential administration are political and designed to achieve their preferred outcome. For the Trump Administration, the choice of the very low social cost of carbon was designed to justify doing nothing about climate change and letting people in the future (including you and your kids) bear the brunt of the resulting unchecked climate impacts.

When the Biden Administration assumed power in early 2021, one of their first actions was to reinstate the Obama value of the social cost of carbon. This value is below the actual cost of emissions that many economists believe new research justifies, and the Administration has indicated that it is a temporary value to be used while a more complete analysis is done.

10.6 Chapter Summary

- Exponential growth means that the rate of growth is directly proportional to the present size. Anything growing at “ x percent per year” is growing exponentially.
- A quantity P growing at r percent per year will grow to $P(1+r/100)^n$ after n years. The time for a quantity growing exponentially to double is frequently referred to as the doubling time; it is approximately equal to $72/r$, and this shortcut is known as the “rule of 72.”
- Exponential growth tends to be end-loaded, meaning most of the growth occurs at the end: 50 percent of the growth occurs during the last doubling period, and 97 percent of the growth occurs during the last five doubling periods.
- People are very bad at intuitively understanding the consequences of exponential growth. When things are growing exponentially, disaster is frequently closer than you think.
- In general, money in the future is worth less than money today. Discounting refers to the process of accounting for this by calculating the present value of some future expense or benefit. Such calculations require a discount rate, which is the rate at which money loses value in the future.
- The discount rate is determined by two judgments: the time discount rate, which is our preference for consuming now rather than later, and the growth discount rate, which reflects the fact that future generations are expected to be richer so they can pay a bigger share of the costs. Economists disagree over what discount rate we should use.
- The social cost of carbon is the cost, discounted to today, of the future impacts due to the emission of 1 tonne of carbon dioxide to the atmosphere. It can be used to evaluate different climate policies by estimating the cost to our economy of carbon dioxide emissions in different policies.
- The social cost of carbon is a highly uncertain quantity, due to uncertainty in the discount rate and difficulty in assessing the monetary value of climate change impacts. Despite the uncertainty, we can be confident that there are net costs to climate change, and these costs could potentially be very large. In 2013, the Obama Administration selected a value of \$36 per tonne of carbon as our best estimate of the social cost of carbon.
- The Trump Administration came up with much lower values of the social cost of carbon by using a higher discount rate (7 percent) and by only counting climate impacts in the United States.

See www.andrewdessler.com/chapter10 for additional resources for this chapter.

TERMS

Discounting
Discount rate
Doubling time

Exponential growth
Growth discounting
Interest rate
Malthus, Thomas
Present value
Rule of 72
Social cost of carbon
Time discounting

PROBLEMS

1. You invest \$1 at a 10 percent interest rate for 50 years.
 - (a) Use Equation 10.1 to calculate how much you have after 50 years.
 - (b) How many doubling periods does the investment experience?
 - (c) Use Equation 10.2 to calculate how much you have after 50 years.
2. You invest \$50 at a 7 percent interest rate for 30 years.
 - (a) Use Equation 10.1 to calculate how much you have after 30 years.
 - (b) How many doubling periods does the investment experience?
 - (c) Use Equation 10.2 to calculate how much you have after 30 years.
3. (a) How many doubling periods do you have to wait for 1 cent to grow to \$100 trillion?
(Calculate to the nearest integer.)
(b) At an interest rate of 7 percent, about how long does it take for that many doublings to occur?
4. Would you rather pay \$1 trillion dollars of damages from and adaptation to climate damage in 50 years or pay \$50 billion dollars today to reduce emissions and avoid the climate change? Use discount rates of 1 percent, 2 percent, 4 percent, 6 percent, and 8 percent.
5. You go into a big-box electronics store to buy a flat-screen television. You have two options: pay \$1,400 today or \$1,450 in 1 year. Which do you choose? You have to estimate a discount rate to do this. How did you choose your discount rate?
6. Lotteries often give you the option of taking a lump-sum payment now or a fixed amount every year for, say, 25 years. For this question, assume that the lump-sum payment is \$3 million, and the yearly payments are \$250,000 each year for 25 years. The first payment is made immediately, so it is not discounted, and subsequent payments are made every year thereafter. You may have to use a spreadsheet program like Excel to do this.
 - (a) Find the discount rate where the present value of the 25-year cash stream is equal to the lump-sum payment.
 - (b) If your discount rate is higher than this, should you take the lump-sum payment or the period payments?

7. In the National Football League draft, a pick in this year's draft is worth a pick in a lower round in a future draft (e.g., you might trade a second-round pick in this year's draft for a first-round pick in next year's draft). Explain how this is consistent with the concept of discounting.
8. (a) Imagine you have a dollar bill. If you double it, you have two bills. If you double again, you have four bills. If you double again, you have eight bills, and so on. Given that a bill is 0.1 mm thick, how many doublings do you have to go through before you have a stack that reaches from the Earth to the Moon? (The Moon is 360,000 km away.)
(b) How many doublings do you need to get a stack that goes halfway to the Moon?
(c) How many doublings do you need to get 1 percent of the way to the Moon?
9. (a) Consider the choice between paying \$10 million today to reduce emissions that cause climate change or \$1 billion in 100 years to adapt to a changing climate. What would the discount rate have to be in order for these two choices to be equal?
(b) Using that same discount rate, what would be your preference if the expense was in 50 years instead of 100?
10. You are inside the Houston Astrodome, in the rafters just below the roof, 160 ft above the field. A wizard puts a tiny magic drop of water on the pitcher's mound, and the drop starts doubling every minute. After 100 minutes, there is 5 ft of water on the field, and the depth doubles every minute. How many more minutes do you have before the water reaches you?
11. Calculating the cost of climate change.
 - (a) If GDP per person (the affluence term in the IPAT relation) grows at 3 percent per year, how many times larger than today will it be after 100 years?
 - (b) Imagine that addressing climate change reduces economic growth from 3 percent to 2.9 percent over the century. How much smaller is our GDP per person in 100 years?
 - (c) How many additional years of growth at 2.9 percent need to occur until the GDP per person is as large as 100 years of growth at 3 percent?
 - (d) Put yourself in the shoes of a future citizen: Given how much richer people will be in 100 years (that is the answer to part (a)), should we be concerned about the loss of wealth due to a reduction in growth from 3 percent to 2.9 percent that we calculated in part (b)?
12. Imagine that you can save the polar bears if you pay a fee every year. If you do not pay the fee, they go extinct. How much would you pay each year to keep polar bears alive?
13. Imagine that there are 1,000 people in the world infected with coronavirus. If the doubling time for coronavirus is 3 days, how many days until the entire world is infected? Assume there are 7.8 billion people in the world.
14. Imagine that there are 1,000 people in the world infected with coronavirus. We're going to estimate how the number of infections increases for doubling times of 2.5 and 5 days.
 - (a) Before doing any calculations, what does your intuition tell you about how different the number of infections will be after 50 days for these two doubling rates? Make a guess as to how many more will be infected when the doubling time is 2.5 days.

- (b) Calculate how many people are infected after 50 days if the doubling time is 2.5 days.
- (c) Calculate how many people are infected after 50 days if the doubling time is 5 days.
- (d) Was your intuition in part (a) accurate?

15. Figure 8.2 showed growth of the drivers of emissions under the various SSPs. For the low-growth SSP3, the affluence term increases from about \$10,000 per person to \$22,000 per person between 2010 and 2100. For the high-growth SSP5 scenario, it increases from \$10,000 per person to \$138,000 per person. Estimate the rate of growth of affluence (percent per year) in these two scenarios.

In the previous chapters of this book, we have seen that (1) the Earth is warming, (2) human activities are the dominant cause, (3) warming over the next century will likely be a few degrees Celsius, and (4) such warming carries with it a risk of serious, perhaps even catastrophic, impacts for humans and the planet's ecosystems.

Given those facts, what shall we do about climate change? Science, it turns out, is just one of several factors needed to answer this question. Deciding what to do also requires information about the options available to us to respond to climate change, and the costs, benefits, and risks of each option. We should also consider the moral implications of each policy. In this chapter, I will outline the various options available to us to address climate change.

Our responses to climate change can be broadly split into four categories: adaptation, mitigation, solar radiation management, and carbon dioxide removal. *Adaptation* means responding to the negative impacts of climate change, which we touched briefly on in Chapter 9. If climate change causes sea-level 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 climate change in the first place, thereby preventing impacts such as sea-level rise from occurring. This is accomplished by reducing emissions of greenhouse gases, usually through policies that encourage the transition from fossil fuels to energy sources that do not emit greenhouse gases.

Solar radiation management refers to active manipulation of the climate system in order to reduce E_{in} , the amount of sunlight being absorbed by the Earth system. If our society continues adding greenhouse gases to the atmosphere, but the amount of sunlight absorbed by the climate system is reduced at a carefully calibrated rate that cancels the increase in greenhouse gases, we could stabilize the global-average climate despite continuing emissions of greenhouse gases.

Carbon dioxide removal refers to active manipulation of the carbon cycle in order to hasten the removal of carbon dioxide from the atmosphere. Under this approach, our society would remove carbon dioxide from the atmosphere as fast as (or even faster than) humans are adding it. This would prevent the amount of greenhouse gases in our atmosphere from increasing, despite continuing emissions, thereby slowing, stopping, or even reversing the warming trend. In the rest of this chapter, we explore these options in detail.

11.1 Adaptation

As we saw in Chapter 2, climate change is already happening, and even under the most optimistic scenario examined in Chapter 8, the climate will continue changing for decades.

To the extent that we do not avoid climate change, we need to adapt to it. Thus, adaptation necessarily *must* be part of our response to climate change. We first discussed adaptation in Subsection 9.3.2, and you may want to review that material if you've forgotten it.

When considering to what extent we should rely on adaptation, we need to first decide how much we want the government involved. At one limit, the government can do nothing and leave it up to individuals to decide how to adapt. If climate changes in agricultural areas, for example, farmers will not just sit there and go bankrupt. Rather, they will take actions necessary to continue farming. For example, they can change farming practices by switching to drought-resistant varietals, add infrastructure to irrigate their fields more effectively, or take any number of similar actions to adjust to the realities of a new climate.

While leaving adaptation up to the individual may be attractive to small-government devotees, it has the significant disadvantage that many adaptive responses take enormous resources or require large-scale societal coordination. Consider, for example, building a seawall. No single individual can build a seawall to protect just their house. Effective seawalls cover an entire community and therefore require consensus from that community on whether to make that significant investment.

Because of this, many of our possible adaptive responses require a significant role to be played by the government. There is a clear need for the government in organizing decisions as well as in providing money and technical expertise. If the government does nothing and leaves adaptation up to individuals, that will severely limit the options people have to adapt. If you live in New Orleans, for example, and the government does not help build flood infrastructure like levees, it would limit your options to moving out of the city or to staying there and trying to protect your individual house (e.g., by raising it), or not doing anything and living under constant threat of being flooded.

Because of this, it is generally agreed that effective adaptation requires involvement of national governments and international institutions, particularly by providing financial resources. And such national or international assistance to a local community often makes sense. If sea-level rise submerges Miami and the resulting economic disruption hurts the entire US economy, then the US federal government might be justified in paying for seawalls to prevent that from happening. Or if climate impacts in India threaten to destabilize the world economy, international assistance to help India deal with the impacts may be appropriate.

In addition to direct aid, governments can also implement regulations 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 eliminate existing regulations that encourage us to be poorly adapted to the present climate and that increase our vulnerability to climate change. A good example is flood insurance. People love to build houses near bodies of water, such as the ocean. However, the downside of this is that flooding may occasionally destroy their houses. Without flood insurance, many people would find it too risky to build in flood-prone areas because they could not afford to have their house destroyed. With flood insurance, however, people can afford to live in flood-prone areas; if their houses are

destroyed by flood, the insurance covers the loss. In this way, flood insurance actually encourages people to build where it is going to flood.

A third way in which government policy can facilitate adaptation is by providing reliable information about climate change. Telling people that the parcel of land they're considering building a house on will likely flood in the next few decades may convince them to build elsewhere. Such information would help people plan for climate change and adapt in advance rather than waiting for disaster to strike and then dealing with climate change. The government can also provide information and technical assistance about possible responses to climate change – e.g., helping a farmer find a drought-resistant variety that is better adapted to a drier climate.

Because many adaptative responses require large resources, the poorest and most vulnerable are also the least able to adapt. While a rich country, like the United States, has resources to build seawalls around vulnerable cities, poorer countries do not. Those countries – whose citizens live on a few dollars a day – are often unable to provide sufficient resources for their citizens today and have no ability to spend money on climate infrastructure.

Even within a rich society, the ability to adapt to the impacts of climate change can vary strongly between the richest and poorest. This was ably demonstrated when Hurricane Katrina hit New Orleans in 2005. When the storm hit, the wealthier residents of New Orleans, those with resources such as credit cards and automobiles, simply left town. The poorest residents of the city, who lacked resources to evacuate, were stranded in New Orleans and made up the vast majority of those killed.

Once the storm passed, the wealthier residents of New Orleans had the resources to reconstruct their lives – either to return and rebuild or to start anew somewhere else. The poorer residents had to rely on government assistance. Because the United States is rich, it was able to provide assistance such as money and temporary housing that kept Katrina from being the much larger humanitarian disaster it would have been for a poorer country.

We also see connections between vulnerability and wealth in two recent earthquakes. In early 2010, a magnitude-7.0 earthquake ravaged Haiti. It killed more than 200,000 people, made 1 million people homeless, and heavily damaged much of the country's built structures. A few weeks later, a magnitude-8.8 earthquake hit Chile. Although this earthquake was 500 times stronger, it killed just a few hundred people. Much of the difference in death toll can be attributed to Chile's greater wealth. Richer countries have the luxury of spending more money on infrastructure, so buildings in Chile were built to more stringent standards, and most did not collapse during the quake.

This means that relying primarily on adaptation as our response to climate change presents us with a difficult reality. The world's richest citizens may be able to adapt to climate change, but the global poor almost certainly cannot. This in turn means that adaptation fails a fundamental fairness test. The world's rich economies have built their wealth by consuming vast amounts of energy, which means that these economies are responsible for most of the global warming over the past two centuries. Yet their very richness allows these countries to deal most effectively with the impacts. The poorest countries in the world are responsible for very little climate change, yet they are least capable of dealing with the impacts.

One solution is for the rich world to help the poor world adapt by giving them resources to adapt. While many of the world's rich countries do give aid to poorer countries, evidence suggests that the rich may not be willing to give enough to help the poor successfully adapt. For example, in 2019 both the US and Australian governments refused to contribute to the international Green Climate Fund, which funds adaptation efforts in poor countries. If the rich world does not help the poor adapt, then a policy that relies on adaptation as our principal response to climate change would abandon the poorest people in the world to the impacts of climate change that they did not cause. The net result of that would be large-scale suffering.

It is worth pointing out that much of what I wrote above depends on your definition of "successful" adaptation. If you define successful adaptation as minimal survival of the human species, then humans can successfully adapt to almost any climate change. After all, we are a resilient species, and it is hard to believe that any climate change will lead to our extinction.

A more realistic standard of success is maintenance of our standard of living as measured by some statistic such as GDP. It seems likely that this is attainable by the rich world if the warming is in the bottom half of the range predicted for the twenty-first century (Figure 8.4). But if warming is in the upper range of predicted warming, then it is very possible that the cost of adapting could significantly impoverish even today's richest countries.

The most expansive definition of adaptation is keeping the world looking pretty much the way it does today, with the same distributions of ecosystems that we have today. If that's your standard of adaptation, then I have some bad news for you – that ship has sailed. Even with the 1°C of warming we already have, we can see the planet changing in important ways. By the time many of you retire, some parts of the planet, particularly those at high latitudes, may be nearly unrecognizable.

The bottom line on adaptation: Because some future climate change is unavoidable, adaptation must be part of our response. But relying primarily on adaptation is problematic because adaptation requires resources, and many of the world's poorest inhabitants have few resources and therefore little ability to adapt. As a result, even low-to-moderate climate change will impose harsh impacts on the world's poor. Many view this as morally unacceptable because the world's poor have contributed little to the problem of climate change.

Rich countries have more resources to address the problem, and for low-to-moderate climate change they may well be able to successfully adapt. But if climate change is at the upper end of the range of predictions discussed in Chapter 8, even rich countries may not have enough resources to adapt. Thus, relying primarily on adaptation as our response to climate change is a titanic gamble for the rich that climate change over the next century will not be severe. For the poor, it is no gamble at all – climate change will impose significant hardships.

Clearly, we should aim to keep future warming as low as possible. In the next section, we talk about how we can accomplish that.

11.2 Mitigation

11.2.1 How to Mitigate Climate Change

Mitigation refers to reductions in emissions of carbon dioxide and other greenhouse gases, thereby preventing the climate from changing in the first place. Because relying entirely on adaptation is a risky strategy, most policymakers view mitigation as the centerpiece of any realistic climate change policy. There are several approaches that could be used to reduce emissions, and I discuss the range of available options in this section.

In Chapter 8, we explored the factors that control emissions of greenhouse gases: population, affluence, and technology. Thus, we can recast the problem of reducing emissions into the problem of reducing one or more of these factors until emissions reach a desired value. The first factor is the world's population. With fewer people on the planet consuming goods and services, emissions would certainly decrease. Some societies have already implemented policies to actively influence the size of their population. China, for example, adopted a "one-child policy," which limits the number of children a family can have to one, although there are many exemptions. This policy has significantly reduced China's population growth rate, although the total population is still increasing.

Reducing emissions through population control would require more than just a reduction in the rate of population growth – it would require a significant reduction in the actual number of people on the planet. Such an effort would conflict with deeply held religious, social, and cultural traditions surrounding reproduction and family size in many countries. It also creates other demographic and societal problems, as China has discovered in response to its one-child policy. As a result, efforts to combat climate change by using policies explicitly targeted at reducing the Earth's population are viewed as politically impossible, and there are no serious discussions of this approach.

A second option is to reduce the world's consumption of goods and services. If each person consumed less, the amount of energy consumed, and therefore emissions, would decrease. Like population, solving the climate problem by reducing consumption would require not just stopping growth of consumption but deep reductions in it. There are several problems with solving climate change this way. First is a political problem – people equate consumption with well-being. That is why all politicians strive for increased consumption (which they call economic growth), and no politician who wants to keep their job would agree to a policy that steeply reduces it. Thus, reducing consumption is something that most countries simply will not agree to.

Then there are the 2 billion or so of the world's poorest inhabitants who live in extreme poverty, on just a few dollars per day. These people do not have the basic necessities of life – food, clean water, shelter – and lifting them out of poverty requires economic growth, meaning increased consumption. Efforts to limit consumption to address climate change might mean preventing these people from escaping poverty. Such an outcome is viewed as morally unacceptable: We cannot solve climate change on the backs of the world's poorest people.

Thus, like population control, there are no serious efforts to address climate change by reducing the world's level of consumption. The rich world does not want to do it, and it is ethically problematic to impose such a policy on the world's poor.

If neither population nor consumption has any chance of being reduced, then by process of elimination it is the technology term, also referred to as the greenhouse-gas intensity, which must be reduced in order to reduce emissions. As I discussed in Chapter 8, the technology term is a measure of how much greenhouse gas is emitted per dollar of GDP, which itself can be broken into two constituent terms: The energy intensity, a measure of how much energy it takes to generate a dollar of GDP (J/\$), and the carbon intensity, a measure of how much greenhouse gas is emitted to generate a joule of energy (CO₂/J). If your memory of this is hazy, you may want to review Chapter 8.

Reducing greenhouse-gas intensity therefore requires reducing energy intensity, carbon intensity, or both. Energy intensity is determined to a large extent by the efficiency with which the economy uses energy. Today's society wastes a tremendous amount of energy, and improving our energy efficiency would not only reduce our emissions of carbon dioxide but would have many co-benefits, such as saving us money. Because of the co-benefits, energy-efficiency improvements would make sense even if climate change were not a problem.

Can efficiency improvements lead to large enough reductions? Probably not. Historically, energy intensity has decreased at 1–2 percent per year. This can likely be maintained, and some improvement may be possible, but, as we will see in Chapter 14, such a rate of decline of energy intensity will not generate the required reduction in emissions. So although improvements in energy efficiency can contribute to emissions reductions and are something we should be doing now, they are likely only going to play a supporting role in solving the climate problem.

11.2.2 Technologies to Reduce Carbon Intensity

We therefore conclude that it is reductions in the carbon intensity term, the amount of carbon dioxide emitted per joule of energy generated, that are required to solve the climate problem. Reducing carbon intensity is code for switching from fossil fuels to energy sources that do not release greenhouse gases – often referred to as *carbon-free* or *climate-safe* energy sources. These include nuclear energy, carbon capture and sequestration, and energy sources known as *renewable energy*, because these energy sources are not depleted when utilized: primarily hydroelectric, solar, wind, geothermal, and biomass energy.

Solar energy is one of the most frequently discussed renewable energy sources. There are actually two different ways to generate energy from sunlight: solar photovoltaic or solar thermal methods. Photovoltaic energy is the most common form of solar energy, and you can see it in operation in the form of solar panels located on houses or other buildings. It takes advantage of the fact that, when exposed to light, certain materials generate electricity. Solar thermal energy, in contrast, uses mirrors to concentrate sunlight on a working fluid (such as an oil, molten salt, or water), heating it to several hundred degrees Celsius. This hot fluid boils water and generates high-pressure steam that is used to turn a generator, producing electricity.

Solar energy is in many respects the Holy Grail of renewable energy. As we calculated in Chapter 4, the amount of solar energy falling on the planet is staggering – more than 100,000 TW. This is an enormous amount of energy compared to the amount humans consume, about 15 TW. One issue with solar is the area required. Taking into account the intermittency and other efficiency issues, solar energy can supply power at a level of approximately 10–20 W/m². To satisfy all human energy needs would therefore require roughly 1 million km² to be covered with solar energy collectors – a square 1,000 km on a side – corresponding to 0.2 percent 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 the number of collectors needed for that much solar energy.

Another frequently mentioned renewable energy source is wind. This is a mature technology – the Dutch have been using wind energy for hundreds of years to do useful work, such as pumping water. Today’s electricity-generating windmills, usually referred to as wind turbines, are quite a bit larger and more sophisticated. These wind turbines get larger every year, but when this was written in 2020, the largest ones had rotors that were 160 m in diameter – nearly two football fields. A single one of these wind turbines can generate as much as 10 MW of power, so that a few hundred are equivalent to a conventional fossil fueled power plant. Technological development of wind turbines is rapid, so, by the time you read this, wind turbines may be even larger and more powerful.

Taking into account the intermittency of wind, satisfying human energy requirements would require wind farms containing 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. One of the most promising places to put wind turbines is offshore. Such installations require no land at all, and the wind blows more consistently offshore, so intermittency is less of an issue than for land-based wind.

Wind and solar energy have been growing rapidly over the recent past 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 with 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.

There are, however, problems with the large-scale adoption of solar and wind energy. The primary one is intermittency – the Sun shines only during daytime and when not obscured by clouds, and the wind speed varies with meteorological conditions. But people want energy when they flip the switch, so wind and solar need to be combined with other technologies to ensure that power is always available.

Biomass energy is another renewable option; it refers to the process of growing crops 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 long-term increase in carbon dioxide in the atmosphere. It is an intuitively attractive energy source, but there are several issues that must be considered. First, the rate of photosynthesis limits the power generated by biomass to roughly 0.6 W/m² of farmed land. Thus, to

generate 15 TW would require that 15 percent or so of the land surface be devoted to growing biomass for energy – comparable to the area under cultivation today.

The enormous land requirement is problematic. We know from experience that much of the additional land will come from clearing forest. This deforestation releases carbon dioxide into the atmosphere, and it causes a host of other local environmental impacts, such as loss of native biodiversity and ecosystem degradation. The second problem is that the farming methods used to grow the biomass have to be carefully considered. Production of fertilizer, for example, requires large inputs of energy, usually from fossil fuels. If fertilizer is used in the growth of the biomass, it might take as much fossil fuel energy to grow the biomass as is saved by substituting the biomass for fossil fuels.

Finally, it is becoming clear that using food, such as corn, as feedstock for biomass energy stresses the food supply. In particular, the increased competition for food raises food prices, an impact disproportionately felt by the poor. The hope is that a technological breakthrough will allow us to produce energy from waste biomass that does not have other uses, such as the waste from corn processing (corn stalks and corn cobs) or cellulosic biomass such as switch grass. Many scientists are currently working on methods to produce biomass energy from these waste sources. Despite these difficulties, biomass, particularly in the form of corn-based ethanol, already provides a few percent of US motor fuels.

Biomass energy systems are a promising technology, but any biomass system must be carefully constructed from end to end to ensure that carbon emissions are actually reduced (e.g., limiting how much fertilizer is used, and where the land comes from). In addition, new technologies that allow biomass energy to be extracted from non-food biomass must be developed. Thus, large-scale biomass energy production may be further in the future than more mature renewable technologies.

Hydroelectric energy is generated when water running through a dam spins turbines and generates electricity. It is the most widespread renewable energy source in the world today, providing 16 percent of the world's electricity. Despite the many advantages of this energy source, it seems unlikely that it can be greatly expanded. Many of the world's big rivers are already dammed, and new dams often cause local environmental problems that generate significant local political opposition.

One of the most contentious options for reducing greenhouse-gas emissions is nuclear energy. Currently, nuclear reactors generate nearly 16 percent of the world's electricity. Although nuclear energy is not technically a renewable energy source, with the technology to recycle and reprocess spent nuclear fuel, there are centuries' worth of uranium in the ground, even assuming a massive expansion of the world's nuclear generation capacity. Nuclear is a mature technology, so there is no question about its technical feasibility.

Opponents of nuclear energy make several arguments against this form of energy. The first is reactor safety, a problem dramatically demonstrated by the 1986 meltdown of a reactor at Chernobyl, during which errors by the operators caused an explosion and fire in a nuclear reactor, or the explosions at a reactor in Fukushima, Japan in 2011, after a tsunami damaged the plant. Releases of radioactivity in both accidents resulted in environmental catastrophes in the regions around the reactors. In addition, nuclear power plants present

attractive targets to terrorists – as anyone who’s ever seen an episode of the TV show 24 will understand – and the prospect of an attack large enough to breach the reactor core and release its radioactive contents to the atmosphere is truly scary.

Another problem is nuclear waste, which is what comes out of the reactor after the nuclear fuel is burned. This waste is extraordinarily radioactive, and it must be safely isolated for tens of thousands of years. If it were released accidentally, or intentionally in a so-called dirty bomb, the resulting harm in both human cost and ecological damage could be massive. One way to reduce the quantity of waste is to reprocess the fuel, in which usable isotopes of plutonium and uranium are removed and converted back into fuel for another trip through the reactor. Even with reprocessing, though, some waste must be stored for a very long time – and most people do not want the waste to be stored near them.

This leads us to the problem of proliferation. A nuclear bomb requires only a few kilograms of uranium or plutonium. As reactor fuel is mined, enriched, and reprocessed, there exists the possibility that small amounts of bomb-grade uranium or plutonium could be diverted with the intent of building a nuclear bomb. The diversion could occur by theft from a legitimate nuclear program, or it could be the explicit (but unstated) goal of a country’s nuclear power program. The net result would be a nuclear weapon in the hands of terrorists or rogue nation, which would present a significant security threat to the rest of the world. This is why the United States and many other countries are opposed to Iran’s development of a nuclear energy program.

Finally, there is the cost. Although nuclear power plants are relatively cheap to run, they are extraordinarily expensive to build. This is one of the primary reasons that no new nuclear power plants have been built in the United States in several decades. It may be that nuclear energy cannot be widely deployed without the government playing a key role in financing the construction.

A final option to generate energy without emitting carbon dioxide to the atmosphere is known as *carbon capture and storage*, also known by its initials CCS, or *carbon sequestration*. This refers to a process by which fossil fuels are burned in such a way that the carbon dioxide generated is not vented to the atmosphere. Rather, the carbon dioxide is captured and placed in long-term storage. CCS is a climate-safe technology but is not renewable (because you are ultimately just burning fossil fuels).

CCS is almost always used in combination with coal combustion because coal is abundant and produces large amounts of carbon dioxide per joule of energy. An example of a CCS technology is to expose the coal to steam and carefully controlled amounts of air or oxygen under high temperatures and pressures. Under these conditions, atoms in coal break apart and react with the water vapor, producing a mixture of hydrogen, carbon dioxide, and several other gases. The carbon dioxide is separated out, and the other gases are burned in order to generate electricity.

Once captured, the carbon dioxide must be stored. The most promising place to store the carbon dioxide is to inject it deep underground into porous sedimentary rocks, which are widely distributed around the world. Particularly promising sites include depleted oil and gas fields, unminable coal beds, or deep saline formations. This process is technically feasible and would use many of the same technologies that have been developed by the oil and gas

industry to enhance the recovery of oil from aging fields. The capacity of these rocks is large enough that they could conceivably hold all of the carbon emitted by human activities.

Using available technology, approximately 85 to 95 percent of the carbon dioxide produced can be captured. This comes at a price, however. A power plant equipped with a CCS system would need to divert 10 to 40 percent of the energy generated into capturing and storing the carbon. Thus, adding CCS would add a few cents per kilowatt-hour of electricity (onto a price in the United States of 10 to 20 cents per kilowatt-hour).

The world has copious reserves of coal, and in our never-ending quest for power, this coal may eventually be burned. CCS may be the only way to both burn this coal and avoid climate change. However, although CCS is a promising technology, no large power plant using CCS has ever been built, so the approach remains unproven.

Finally, the climate-safe energy discussed in this section is not an exhaustive list. There are other energy sources not discussed, such as geothermal, that may turn out to be important, especially in some locations.

Given the abundant resources and rapid technological development, it seems likely that we will eventually be mainly powered by solar and wind energy. As mentioned above, the main issue is intermittency – there will be times when neither is generating as much power as is required.

There are several different ways to ensure the reliable 24-hour availability of power that consumers expect. One way is to store energy, which would allow energy generated at one time to be sent to consumers at some later point in time. To do this, you could do something obvious, like build an industrial-scale battery. There are also less obvious solutions, such as making hydrogen (by splitting water molecules) when excess energy is available, storing the hydrogen, and then converting the hydrogen back to electricity by burning it when the electricity is needed.

Another way to solve intermittency is to build more long-distance transmission capacity. While the Sun may not be shining where you are, or the wind blowing, the Sun is always shining and the wind is always blowing somewhere. If we could transmit power long distances, then even if no renewable energy was being generated in your vicinity, you could still have access to renewable energy.

Intermittency also becomes a much smaller problem if a fraction of our energy mix is dispatchable carbon-safe energy. Dispatchable power refers to energy sources that are available at any time and can be dispatched at the request of the electric grid operators. This includes always-on energy sources like hydroelectric, geothermal, or nuclear. The combination of solar and wind energy, energy storage, an enhanced grid, and dispatchable climate-safe energy would allow us to move entirely away from fossil fuel energy in our energy system.

11.2.3 Time Scale of Mitigation

It is very important to realize that, once you start mitigating, you may not see results for decades. This occurs because the lifetime of carbon dioxide is so long that carbon dioxide

is essentially just accumulating in the atmosphere. It can therefore take a while for changes in emissions of carbon dioxide to significantly change the amount of carbon dioxide in the atmosphere and for this to then show up in the global temperature. For example, Figure 8.4 showed that temperatures predicted for the various emissions scenarios do not diverge until around 2050, despite the fact that emissions in the scenarios diverged decades earlier (Figure 8.2).

Because of this, mitigation requires costs now to derive benefits several decades in the future. Humans are terrible at these kinds of trade-offs and frequently avoid taking prudent actions now even when they know they'll suffer much worse repercussions later if they don't. In this case, convincing people to take action on climate when the benefits are decades away is a steep political challenge. That's especially true when many of the people being asked to pay to mitigate will not live to benefit from the reduced temperatures later.

The bottom line on mitigation: Almost everyone agrees that mitigation should be the centerpiece of our efforts to avoid dangerous climate change. Although there are many ways to reduce emissions, the only practical way is to reduce our carbon intensity by rebuilding our energy system to primarily use climate-safe energy sources instead of fossil fuels. These climate-safe energy sources will certainly include wind and solar, but also may include nuclear, carbon sequestration, biomass, and others.

11.3 Solar Radiation Management

The final two solutions to the climate change problem, solar radiation management and carbon dioxide removal, involve actively manipulating the climate system in order to stop the climate from changing. Their basic premise is that we could continue burning fossil fuels and emitting carbon dioxide into the atmosphere but make other changes to the Earth system that effectively canceled these emissions.

These two responses are sometimes lumped together and referred to as *geoengineering*, climate engineering, or climate intervention. However, I've concluded that there are enough differences between them that they belong in separate categories. In this section, I'll focus on *solar radiation management*. This term describes efforts to engineer a reduction in the amount of solar energy absorbed by the Earth, E_{in} . If done in a carefully calibrated manner, this would cancel the increase in greenhouse gases in our atmosphere, which would stabilize the climate.

Since $E_{in} = S(1-\alpha)/4$, where S is the solar constant and α is the albedo (if you do not remember this, you should review Chapter 4), we can reduce E_{in} by either decreasing S or increasing α . Decreasing S , while not impossible,¹ is hard, so most solar radiation

¹ Some people advocate putting mirrors in space between the Earth and Sun to reflect away a small fraction of incoming solar energy.

management schemes aim to increase the Earth's albedo. The most frequently discussed way to do this is to inject aerosols into the atmosphere (aerosols are solid or liquid particles that are so small that they have negligible fall speed; they were discussed extensively in Chapter 6).

One way to do this is to inject sulfur dioxide (SO_2) into the stratosphere. Once in the stratosphere, this gas reacts with water vapor to form sulfate aerosols. These aerosols reflect sunlight back to space, thereby increasing the albedo of the Earth and leading to cooling. Injection of sulfur into the stratosphere is the same mechanism by which volcanic eruptions cool the planet.

Another option is to increase the reflectivity of low clouds. As discussed in Chapter 6, the size of the cloud droplets determines how white a cloud is, with smaller cloud droplets making a cloud whiter and more reflective. This is the same reason that powdered sugar, which is made up of small particles, appears whiter than chemically identical table sugar. Thus, if we could somehow make the particles in clouds smaller, clouds would become more reflective and raise the albedo of the Earth.

One way to do this is to release cloud condensation nuclei (CCN) into the clouds (CCN were discussed in Subsection 6.2.2). These nuclei serve as seeds that cloud droplets form around. By adding them to clouds, we increase the total number of droplets in the cloud. Because the total water contained in a cloud is basically fixed, this makes the cloud contain more, but smaller, particles. This effect can be seen in ship tracks (Figure 6.6), which are clouds brightened when particles in the exhaust from ships' diesel engines are transported into low-level clouds.

The physics supporting these suggestions is robust, and we have high confidence that these schemes, carried out at sufficiently large scale, would cool the planet. Additionally, solar radiation management approaches have two other distinct advantages. First, once implemented, temperatures will react immediately. This contrasts favorably with mitigation, for which emissions reductions must begin now in order to head off climate changes that will occur in 50 to 100 years. Second, they will be relatively inexpensive, with costs of perhaps \$10 billion per year to offset the radiative forcing from human emissions. For this same amount, you could get one nuclear power plant, which would make a very small dent in emissions.

There are, however, important disadvantages with solar radiation management. The first is that these schemes focus primarily on temperature, but temperature increases are only one of many impacts associated with climate change – and perhaps not even the most important. We know, for example, that some of the carbon dioxide released into the atmosphere ends up in the ocean, resulting in ocean acidification. Solar radiation management schemes do nothing to address this impact of continued carbon dioxide emissions.

Moreover, solar radiation management schemes may create other problems. The 1991 eruption of Mount Pinatubo, for example, which cooled the climate by several tenths of a degree, also led to substantial changes in global precipitation patterns and an increase in the incidence of drought in some regions. We can therefore expect that solar radiation management schemes would also lead to changes in the amount and distribution of global

precipitation. Whether these changes would be better or worse than climate change is a question whose answer is not clear.

And there are important political problems with this approach. Imagine that a few rich countries in the world (e.g., the United States and Europe) got together to inject sulfur into the stratosphere to cool the planet. Then, China or India experienced a severe drought. Whether the sulfur injection caused that drought or not, the citizens of the countries affected might well believe that it did and insist that their governments take action to stop the sulfur injection. This would lead to a great amount of political tension, possibly even the abandonment of the geoengineering effort. In the worst case, geoengineering by a group of countries might be considered an act of war by another group of countries that suffered some type of weather-related injury at the same time.

The lifetime of aerosols in the atmosphere is a few weeks to a few years. That means that solar radiation management must be continuous. If we ever stopped injecting aerosols into the atmosphere, the atmosphere would clear in a short time and the Earth's albedo would rapidly decrease. This could lead to a rapid rise in the Earth's temperature over the following decade or two – which would lead to terrible impacts. In fact, it would likely be far worse than if we had never started solar radiation management. Thus, once you start solar radiation management, it is difficult to stop.

The bottom line on solar radiation management: This is an appealing but risky approach to dealing with climate change. We have high confidence that we could do it, and it could be implemented quickly and at reasonable cost. However, it would not counteract all impacts of climate change, and it would also present important global governance problems. It could also create new, unforeseen environmental problems. Finally, once the world starts solar radiation management, stopping too soon could result in a very rapid and dangerous pulse of warming.

Because of this, virtually no one advocates solar radiation management as the primary solution to climate change. Rather, its main job will be as a stopgap measure to keep global temperatures from exceeding dangerous thresholds in the event that mitigation efforts start too late or are not sufficient. I will discuss this in more detail at the end of this chapter.

11.4 Carbon Dioxide Removal

Carbon dioxide removal refers to efforts to modify the carbon cycle so that carbon dioxide is rapidly removed from the atmosphere. As we learned in Chapter 5, it takes a few centuries for the natural carbon cycle to remove a majority of carbon dioxide emissions from the atmosphere (complete removal takes about 100,000 years). This is the reason carbon dioxide is such a pernicious greenhouse gas.

Carbon dioxide removal schemes attempt to modify the carbon cycle in order to remove carbon dioxide from the atmosphere much faster than natural processes. Planting trees is an example of carbon dioxide removal. As discussed in Chapter 5, when trees grow, they suck

carbon dioxide out of the air and sequester it in wood. The problem with trees as a carbon storage device is that it is 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.

For carbon removal to be effective, the carbon must be safely sequestered for many thousands of years or longer. One possible scheme is to add iron to the ocean. Iron is thought to be a limiting nutrient there, so the addition of iron will stimulate the growth of phytoplankton. As the phytoplankton grow, carbon dioxide will be drawn out of the atmosphere and into the ocean. The phytoplankton are then consumed by larger organisms, and subsequent biological activity creates a rain of dead organisms and fecal matter from surface waters into the deep ocean. Thus, adding iron to the ocean may have the net effect of drawing carbon dioxide out of the atmosphere and transporting it to the deep ocean.

Another option is to remove carbon dioxide from the air chemically, which is often referred to as *direct air capture*. This is like CCS, but CCS removes carbon dioxide from the hot exhaust gas of a power plant whereas air capture removes carbon from the free atmosphere. There are various ways to do this. Carbon dioxide could be removed from the air by chemical processes, or it could be removed by growing plants and then sequestering the plant carbon. One way to do this, known as bioenergy with carbon capture and storage (abbreviated *BECCS*), is to grow plants and then burn the plants for energy, capture the carbon dioxide produced in combustion, and store it. As with CCS, the most likely place to store the carbon is deep underground in depleted oil and gas wells.

In general, carbon dioxide removal is attractive because, unlike solar radiation management, it does not focus just on temperature. If we balance emissions of carbon dioxide from human activities with carbon dioxide removal, we will truly stabilize the climate – not just temperature, but all aspects, including ocean acidification and precipitation. In fact, a sufficiently aggressive program could lead to a *reduction* in atmospheric carbon dioxide (not just a stabilization), which eventually could undo many of the effects of climate change (but not all – some changes, such as extinction of species, are absolutely irreversible, whereas others, such as loss of the world's largest ice sheets, are irreversible on any time scale that we care about).

There are, of course, some problems with the various approaches to carbon dioxide removal. First, the scale of required carbon dioxide removal is enormous – as discussed in Chapter 8, humans are adding more than 40 billion tonnes of carbon dioxide to the atmosphere every year. It requires a vast infrastructure of wells, mines, pipelines, refineries, etc. worth trillions of dollars to generate such emissions. We can expect that pulling an equal amount of carbon out of the atmosphere will require a roughly equal amount of infrastructure, also costing trillions of dollars and decades to construct.

Some approaches to removing carbon dioxide from that atmosphere, like adding iron to the ocean, could be risky. Because of significant uncertainties in our knowledge of how carbon cycles in the ocean, we might add iron to the ocean only to find out that, because of

unanticipated physics or biology, no extra carbon dioxide was removed from the atmosphere. Even worse, it might have unforeseen and serious impacts on ocean ecosystems. Thus, in trying to address climate change, we may cause an entirely new environmental problem – and not even solve the problem we were intending to address.

The bottom line on carbon dioxide removal: If we could do it, carbon dioxide removal would be a great way of dealing with climate change. In fact, because we've waited so long to address the climate problem, keeping our planet from warming too much will likely require it. However, the ability to remove tens of billions of tonnes of carbon dioxide from the atmosphere and sequester it in a stable reservoir, all at a reasonable price, is entirely speculative. So while we should continue trying to develop this approach, at present we need to focus on the other responses.

11.5 Putting It Together

In this chapter, we have discussed our options for dealing with climate change: adaptation, mitigation, solar radiation management, and carbon dioxide removal. To understand how we might rationally combine these various approaches, consider the following schematic example. Figure 11.1a shows a world without any explicit efforts to address climate change; that world is on track to exceed a temperature threshold beyond which it is judged that dangerous impacts occur. Obviously, we would prefer to keep warming below this threshold.

The first tool in the toolbox is mitigation. If we start early enough, that's all we need to do (Figure 11.1b). Note that we still need adaptation in this world because some climate change still exists and we need to adapt to it. But by mitigating, we can keep warming below the dangerous threshold. It's worth emphasizing that we have to start mitigation when the temperature is well below the threshold because, as discussed earlier, it takes decades for mitigation to bend the temperature curve.

Now let's imagine that we don't start mitigating early enough to avoid the dangerous threshold. As we'll discuss in Chapter 14, this is likely the world that we're living in. In this world (Figure 11.1c), even maximally aggressive mitigation will not keep warming under the limit we set.

In this case, we have to deploy other policy tools. For example, we can use carbon dioxide removal (Figure 11.1d) to reduce temperatures beyond what mitigation alone can achieve. Note that our ability to do this is speculative – we simply have no idea if we can economically pull tens or hundreds of billions of tonnes of carbon out of the atmosphere over a century.

The temperature trajectory in Figure 11.1d has what is known as an *overshoot*, where the temperature temporarily exceeds the dangerous threshold for a few decades before declining back below the threshold. If it turns out that even a temporary exceedance of the threshold produces unacceptable impacts, then we can use solar radiation management to cool the planet during the overshoot (Figure 11.e).

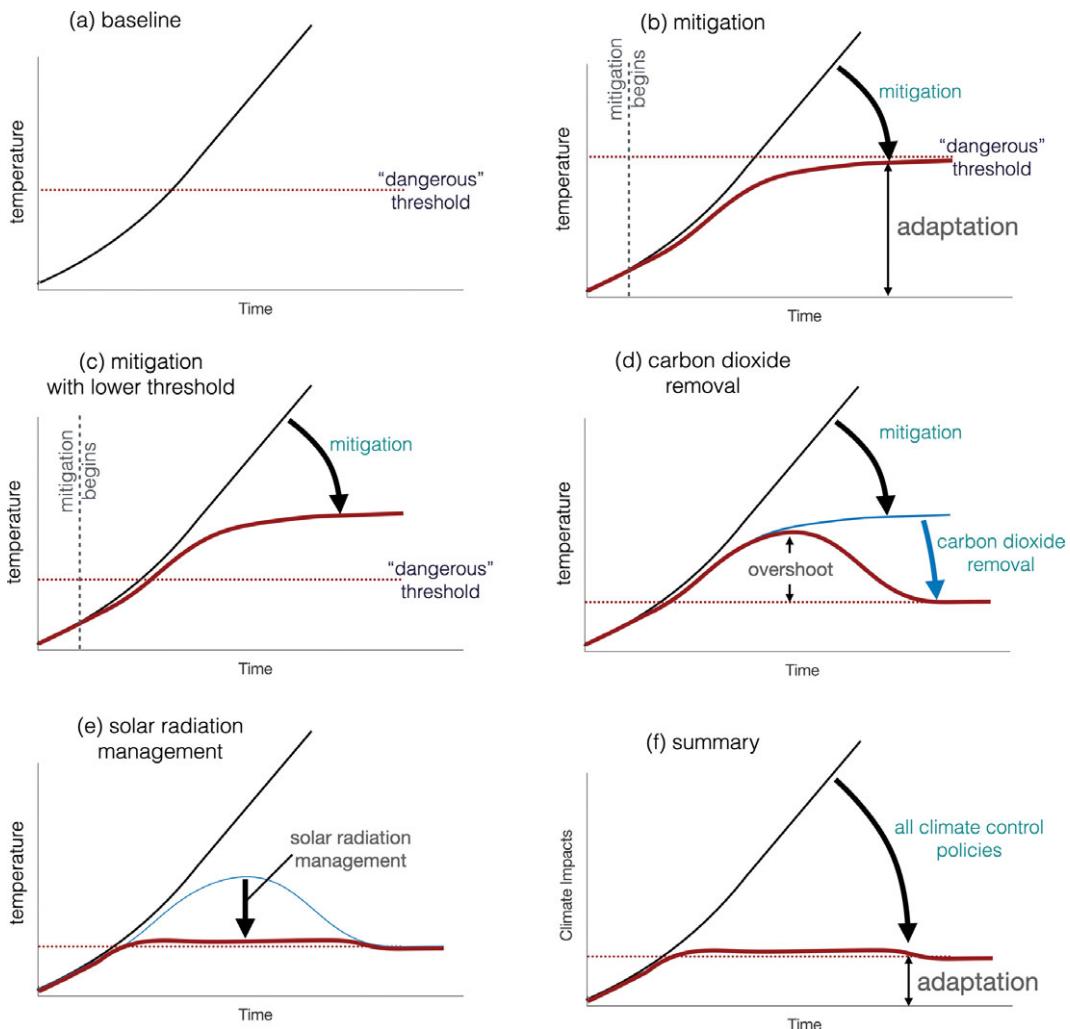


Figure 11.1 Our policy options to respond to climate change. (a) The baseline scenario, in which no effort is made to address climate change. The “dangerous” threshold is the warming limit that we do not want to exceed. (b) A successful climate response for a high “dangerous” threshold that relies entirely on mitigation and adaptation. (c) A climate response for a low “dangerous” threshold where mitigation alone fails to stay below the threshold. (d) A climate response for the low threshold that is composed of mitigation and carbon dioxide removal but has an overshoot. (e) A climate response that includes mitigation and carbon dioxide removal and uses solar radiation management to avoid the overshoot. (f) A summary of the total potential response.

In the end (Figure 11.1f), we can combine our policy tools to keep the temperature from exceeding what we consider to be the dangerous threshold. But don't forget that, even in this scenario, we still need to adapt to some unavoidable climate change.

11.6 Chapter Summary

- Responses to climate change can be roughly divided into four categories: adaptation, mitigation, solar radiation management, and carbon dioxide removal. Solar radiation management and carbon dioxide removal are sometimes combined into a single category called geoengineering.
- Adaptation means learning to live with climate change. Adaptation requires resources, so the rich are far better capable of adapting than the world's poor. This also means that our capacity to adapt is limited, and if climate change falls into the upper end of the predicted range, even the world's richest may not be rich enough to adapt. Because of this, few people advocate relying on adaptation as our primary response to climate change. However, adaptation must be part of our response because not all climate change can be prevented.
- Mitigation refers to efforts to reduce emissions, thereby preventing future climate change. Most experts view mitigation as the primary component of any plan to address climate change. This will be accomplished mainly by transitioning from fossil fuels to energy sources that do not emit greenhouse gases. Because of lags in the climate system, it takes several decades before mitigation efforts have an appreciable effect on the climate.
- Solar radiation management attempts to engineer a reduction in solar radiation absorbed by the planet. The most likely way to accomplish this is to inject sulfur compounds into the stratosphere, where they will form aerosol droplets that reflect a small fraction of sunlight back to space. We know this will work – it's how volcanic eruptions cool the planet – but it is considered a risky approach.
- Carbon dioxide removal attempts to modify the carbon cycle so that carbon dioxide is removed from the atmosphere more quickly than it is by the natural carbon cycle. While there would be few disadvantages to doing this, our ability to remove carbon from the atmosphere at the scale required (billions of tonnes per year) and at reasonable cost is entirely speculative.
- Overall, there is widespread agreement that we need to mitigate, i.e., reduce emissions, as fast as possible. This will limit the warming that we experience. However, we cannot eliminate all warming; therefore we need to adapt to warming that we cannot avoid. If mitigation starts too late to keep warming in check, then solar radiation management and carbon dioxide removal can play a role in buying time for mitigation actions to achieve our objectives.

See www.andrewdessler.com/chapter11 for additional resources for this chapter.

TERMS

Adaptation
BECCS
Carbon capture and storage
Carbon dioxide removal

Carbon-free/climate-safe energy sources
Carbon sequestration
Direct air capture
Geoengineering
Mitigation
Overshoot
Renewable energy
Solar radiation management

PROBLEMS

1. Our responses to climate change can be put into four general categories. List the categories. For each category, give one example of an action that would fall into that category.
2. (a) What are carbon-free energy sources? List several discussed in the book.
(b) Is carbon-free energy the same as renewable energy?
(c) Is nuclear energy carbon free? Is it renewable?
3. (a) Your friend says, “We should rely entirely on adaptation as our response to climate change.” Is this a good idea?
(b) I argued here that adaptation must be at least part of our response. Why?
4. While solar radiation management and carbon dioxide removal are sometimes lumped together under the name “geoengineering,” they are actually quite different approaches. What are the advantages and disadvantages of each of them?
5. (a) Explain one way we can “geoengineer” a higher planetary albedo.
(b) Explain one way we can “geoengineer” a reduction in carbon dioxide.
6. In this chapter, we explored the terms of the IPAT relation (Equation 8.1) and concluded that reducing emissions could really be achieved only through reduction of one term. Which term is it, and why is that our only real option?
7. The technology term in the IPAT relation can be further divided into two terms.
 - (a) For each term, give an example of how to reduce it.
 - (b) One of these terms is the key to deep reductions in emissions. Which one is it? What kinds of changes are required to make such deep reductions?
8. Why do mitigation policies have little ability to influence the climate over the first half of the twenty-first century?
9. As detailed in Section 11.5, under what circumstances does using solar radiation management and carbon dioxide removal make sense?

12 Mitigation Policies

Chapter 11 discussed the options we have to address climate change: adaptation, mitigation, solar radiation management, and carbon dioxide removal. Adaptation will, by necessity, be an important part of our response to climate change. However, relying entirely on adaptation as our only response to climate change is fraught with problems. Geoengineering (solar radiation management and carbon dioxide removal) is another possibility, but one that few people think should be used now. It may help us achieve our climate goals, as we discussed at the end of the last chapter, but no one seriously suggests that it should be our primary way of dealing with climate change.

The remaining option is mitigation – the reduction of greenhouse-gas emissions so as to avoid climate change – and there is strong agreement among those who have looked seriously at the problem that this should be the centerpiece of our efforts to address climate change. Mitigation schemes will likely have little effect on the climate of the next few decades, but a successful mitigation effort would allow us to avoid large climate changes in the second half of this century and beyond.

As we learned in Chapter 11, mitigation basically means we need to convert our energy system from one that burns fossil fuels to one that primarily utilizes carbon-free energy sources, such as solar, wind, nuclear, and CCS. In this chapter, we explore in detail the policy options that governments can use to achieve this. Before we do that, though, it's worth explaining why climate change exists in the first place.

12.1 The Economic Basis of Climate Change

From a physics point of view, climate change is actually pretty simple. Humans are adding greenhouse gases to the atmosphere (Chapter 5), and these gases absorb infrared radiation, which warms the climate (Chapter 4). But you can also explain climate change from an economics point of view. As discussed in Chapter 8, greenhouse-gas emissions are proportional to the value of goods and services consumed by a society. So you can also think of climate change as a side effect of economic activity.

If we know we are causing climate change (we do, as discussed in Chapter 7) and we know it may be bad for us (we do, as discussed in Chapter 9), why do we keep emitting greenhouse gases? There is, after all, abundant evidence that the free market is efficient at allocating resources and producing socially beneficial outcomes (although, as the

occasional economic meltdown shows, it is not perfect). As former US Senator Chuck Hagel said in an interview,¹

I have always believed that the marketplace does work. It works because it's based on one fundamental dynamic, which is self-interest of an individual, a company, or a country. The marketplace fosters competition and always trends toward producing a better, cheaper product, which means it is a driver of efficiency. It's in the interests of everyone here to make a cheaper product that's less energy intensive. It cleans up the environment, which has economic advantages too.

As I'll explain in this section, this argument is fundamentally wrong. Emissions reductions sufficient to stabilize the climate at levels that avoid dangerous climate change will not occur by themselves.

To understand why the free market does not work in this situation, consider the following scenario. Imagine you own a company that produces widgets. Let us assume that it costs your company \$10 to manufacture a widget, and during the manufacture process, some carbon dioxide is released into the atmosphere. This carbon dioxide will cause climate change, which causes damages valued at \$2. Thus, the total cost of manufacturing a widget using this process is \$12. However – and this is important – the widget manufacturer only pays \$10; the costs of climate impacts associated with the widget, \$2, are borne by everyone in the world. At the same time, the benefit of producing the widget goes entirely to the manufacturer.

Economists call the costs of climate change imposed on the rest of the world by the widget manufacturer an *externality*. More generally, an externality is a cost imposed on people who are not part of the transaction, i.e., not the buyer or seller. To understand how externalities distort economic incentives, imagine that someone invents a new process for manufacturing widgets, in which it costs \$11 to produce a widget but no carbon dioxide is emitted to the atmosphere. There are no climate impacts associated with this process, so the total cost is also \$11. Because the total cost of manufacturing a widget under the new process is \$1 cheaper than the total cost for the older process, it would be beneficial to the economy for the widget manufacturer to switch to this new process.

But the widget manufacturer will not switch. The widget manufacturer is only paying \$10 per widget under the older method, with the rest of the cost being borne by society. Under the new process, however, the manufacturer pays the entire cost of \$11. So even though this new process is cheaper to society as a whole, to the widget manufacturer, this new process is more expensive. Thus, because of the externality, the socially and economically preferred outcome does not occur, a result sometimes referred to as a *market failure*.

Externalities and the associated market failures occur frequently in environmental problems in which some profitable economic activity degrades a common asset such as the atmosphere, the ocean, or a river – and the costs of that degradation are paid for by society. In such a situation, the incentive for the polluter is to pollute without regard to the impacts because the costs of pollution are paid by everyone in the society – not the polluter. This is a

¹ www.grist.org/article/hagel/, accessed June 22, 2020.

version of the “tragedy of the commons,” and it is the fundamental economic explanation for why overfishing is depleting stocks of fish in the oceans, logging is destroying the rainforests, and greenhouse-gas emissions are changing the climate.

The free market works because, in most cases, what is in the best interest of individual actors in the economy is also in the best interest of society. But that’s not the case here. Because it is free to load the atmosphere with carbon dioxide, the rational behavior of each emitter is to dump as much greenhouse gas into the atmosphere as is necessary to maximize profit, without regard to the damage being caused to the environment and society *because the emitter is not paying for the damage*.

Therefore, we cannot expect the magic of the markets to fix the problem. Instead, we are left with a conclusion that a lot of people find distasteful: We need government regulation to solve the climate problem. Let me emphasize that our choice is between government regulation and unrestrained greenhouse-gas emissions and the associated climate change. We get one or the other. There is no magical third option where we solve the climate problem without government playing a significant role in the market. In the rest of the chapter, I will describe some of the policies that governments can adopt to reduce emissions, thereby allowing us to avoid dangerous climate change.

12.2 Conventional Regulations

The conventional approach to regulation, often described colloquially as *command-and-control* regulation, requires all emitters in a particular economic sector to meet a single standard. Electricity companies, for example, might be required to generate energy by using a particular technology, such as wind or nuclear, or cars might be required to be electric. Alternatively, regulations may limit total emissions of a pollutant, or enforce a standard of greenhouse gases emitted per kilowatt-hour generated (for power plants) or greenhouse gases emitted per mile driven (for cars). For example, in 2012 the Obama Administration proposed requiring new power plants to emit less than 1,000 pounds of carbon dioxide per megawatt-hour of energy produced. Burning coal produces more than this, so this never-enacted regulation effectively prohibited the construction of new coal-fired power plants (without CCS).

The conventional approach has the advantage that it is clear and easy to understand. Even today, many environmental regulations, including regulations on air pollution, fall into this category. Since the 1980s, however, weaknesses with this approach have been identified, and it has been falling out of favor with regulators. First, technologies specified (e.g., wind) may not actually turn out to be the best ones. Second, the regulations force all emitters to meet the same emissions standards. This ignores the fact that some emitters can reduce emissions more cheaply than others. Third, conventional regulations provide no incentive to reduce emissions beyond the specified target. In cases where it is possible for emitters to cut emissions further at low cost, these regulations will not encourage that behavior.

As we will show below, these disadvantages make conventional regulation more expensive than market-based approaches, described in the next section. Because of this, market-based regulations are generally preferred, and I will spend most of the rest of the chapter discussing them.

12.3 Market-based Regulations

In Section 12.1, I discussed why the free market will not solve the climate problem without intervention from the government: because it is free to dump greenhouse gases into the atmosphere. The cost of the climate damages from these emissions is imposed on everyone, not just the emitter, so there is no economic incentive for the emitter to reduce emissions.

Therefore, to solve climate change, economics tells us that the costs of the damages from the emission of greenhouse gases to the atmosphere must be shifted back onto the emitter. In the parlance of economics, we need to internalize the externality, meaning that emitters must be held accountable for the damage they cause.

In the next two sections, I will discuss the two market-based regulatory approaches most frequently discussed in the climate change policy debate: carbon taxes and cap-and-trade systems.

12.3.1 Carbon Tax

The first approach is a *carbon tax*. This is considered a market-based approach because the government does not tell emitters how much they can emit. Emitters have complete freedom to emit as many tonnes of greenhouse gas to the atmosphere as they choose, as long as they pay a specified fee to the government for each tonne released.

To understand why a carbon tax reduces emissions, let us imagine a power plant, which we will call Plant A, that emits 10 tonnes of carbon dioxide into the atmosphere each year. The third column of Table 12.1 contains the *marginal cost* for reducing emissions for Plant A, which is the cost of reducing a particular tonne of emissions. Thus, Plant A can reduce its annual emissions by 1 tonne – from 10 tonnes to 9 tonnes – for \$1. Reducing emissions another tonne, from 9 tonnes to 8 tonnes, costs an *additional* \$2. Thus, the total cost of reducing emissions from 10 to 8 tonnes is the sum of the marginal costs,² that is, $\$1 + \2 , for a total cost of \$3. The next tonne of emissions costs \$3 to eliminate, so the total cost of reducing emissions from 10 to 7 tonnes is $\$1 + \$2 + \$3 = \6 .

The marginal cost of reducing emissions increases as emissions are progressively reduced. To see why, think about golf. When you just start out, you may be shooting 130 strokes over 18 holes. It takes relatively little effort to reduce your score by one stroke, down to 129 – perhaps only an hour at the driving range. Taking another stroke off your score,

² For those of you who know calculus, you can think of the marginal cost as the derivative of the total cost function and the total cost as the integral of the marginal cost function.

Table 12.1 Cost of reducing emissions for Plants A and B

Emissions reduced by (tonnes)	Units emitted (tonnes)	Plant A's cost (\$)		Plant B's cost (\$)	
		Marginal	Total	Marginal	Total
0	10	—	—	—	—
1	9	\$1	\$1	\$2	\$2
2	8	\$2	\$3	\$4	\$6
3	7	\$3	\$6	\$6	\$12
4	6	\$4	\$10	\$8	\$20
5	5	\$5	\$15	\$10	\$30
6	4	\$6	\$21	\$12	\$42
7	3	\$7	\$28	\$14	\$56

reducing your score to 128, takes slightly more work, maybe two more hours at the driving range. By the time your score reaches 80 and you are getting close to par, it can be extremely difficult and take enormous practice to reduce your score by one stroke to 79. Eventually, you reach a limit which you will never move past, no matter how hard you work.

In this golf example, the marginal cost is the amount of effort you have to apply to reduce your golf score by one stroke. The fact that the amount of work it takes to improve your score by one stroke increases as you get better is a version of the law of diminishing returns: each additional unit of effort (e.g., an hour at the driving range) produces less of an improvement than the previous unit of effort.

For Plant A, fine-tuning the machinery in the plant may reduce the first tonne with very little effort. Once the equipment has been tuned up, however, additional reductions are harder to make. Eliminating the second tonne may require replacing some outdated equipment with newer, more efficient equipment. This will cost more than the first tonne. The third tonne may require even more equipment replacement, or perhaps wholesale changes in the plant's operation. This tonne will therefore be more expensive to eliminate than the previous 2 tonnes.

Now imagine that a carbon tax of \$4 per tonne is imposed on the emitters – meaning that, for every tonne emitted into the atmosphere, the plant has to pay the government \$4. How would each plant respond? Remember that Plant A has total freedom to emit as much as it wants – the carbon tax does not specify any reduction. Plant A will therefore search for its cheapest alternative.

Let's do a tonne-by-tonne analysis and see what Plant A will do. Plant A can emit the tenth tonne and pay a tax of \$4, or it can pay \$1 and not emit that tonne. It does not take a financial genius to conclude that the rational thing to do is not emit the tonne. Now emissions are down to 9 tonnes, and Plant A can emit the ninth tonne and pay a tax of \$4, or it can pay \$2 and not emit that tonne. For this tonne, too, the rational thing to do is not emit that tonne. Now emissions are down to 8 tonnes, and Plant A can emit the eighth tonne and pay a tax of \$4, or it can pay \$3 and not emit that tonne. Again, the rational thing to do is not emit that tonne.

Now things get a bit trickier. For the seventh tonne, Plant A can emit the tonne and pay a tax of \$4 or it can pay \$4 and not emit that tonne. From a purely financial point of view, these two alternatives are equivalent. I suspect, though, that most companies will reduce that last unit because the company can use this to burnish its environmental reputation. So we can assume that Plant A will choose to not emit the seventh tonne.

For the sixth tonne, Plant A can emit the tonne and pay a tax of \$4 or it can pay \$5 and not emit that tonne. The rational thing to do in this situation is to pay the tax and emit that tonne. Thus, under a carbon tax of \$4, Plant A will reduce emissions by 4 tonnes.

Now let us consider a second plant, which we will call Plant B, whose marginal costs are also listed in Table 12.1. Plant B has higher marginal costs for reducing emissions than Plant A. This may arise for any number of reasons – for example, Plant B may be older than Plant A and so be using different technology that makes it more expensive to reduce emissions. Plant B can emit the tenth tonne and pay a tax of \$4, or it can pay \$2 and not emit that tonne. Clearly, Plant B will not emit the tonne.

Now emissions are down to 9 tonnes, and Plant B can emit the ninth tonne and pay a tax of \$4, or it can pay \$4 and not emit that tonne. As for Plant A, we can assume that Plant B will choose to not emit that tonne. Now emissions are down to 8 tonnes, and Plant B can emit the eighth tonne and pay a tax of \$4, or it can pay \$6 and not emit that tonne. Here, the rational thing to do is to pay the tax and emit that tonne. Thus, under a carbon tax of \$4, Plant B will reduce emissions by 2 tonnes.

The total reduction in emissions from the two plants in response to a carbon tax of \$4 per tonne is 6 tonnes: a reduction of 4 tonnes from Plant A and 2 tonnes from Plant B. The total cost to Plant A of reducing emissions is the sum of the marginal costs, $\$1 + \$2 + \$3 + \$4 = \$10$, whereas the total cost to Plant B is $\$2 + \$4 = \$6$. Thus, the total cost to society of reducing 6 tonnes of emissions is $\$10 + \$6 = \$16$.

Under a conventional command-and-control approach, there is a single performance target that each plant is required to meet. An emissions reduction of 6 tonnes might be achieved, for example, by having both Plant A and B reduce emissions by 3 tonnes. This would cost Plant A $\$1 + \$2 + \$3 = \6 to reduce 3 tonnes, whereas it would cost Plant B $\$2 + \$4 + \$6 = \12 to reduce 3 tonnes. The total cost of this 6-tonne reduction is \$18.

This is an important result. The carbon tax of \$4 per tonne resulted in a 6-tonne reduction for \$16, whereas the conventional command-and-control approach resulted in a 6-tonne reduction for a cost of \$18. The carbon tax is cheaper because of its *flexibility* – it shifts reductions to the lowest marginal cost emitters, in this case, Plant A – so that the emissions reductions are made where they are cheapest, which lowers overall cost to society.

To summarize, here are three conclusions you should remember:

- Under a price on carbon, *emitters will reduce emissions until the marginal cost of reduction is equal to the carbon tax rate*. For Plant A, the marginal cost equals the tax rate of \$4 per tonne when emissions have been reduced by 4 tonnes, whereas for Plant B, the marginal cost equals the tax rate when emissions have been reduced by 2 tonnes.

- *Because marginal costs vary among emitters, the lower marginal cost emitters will make deeper cuts than higher marginal cost emitters.* In our example, Plant A, the lower marginal cost emitter, reduces emissions more than Plant B.
- *Because of this, achieving any particular economy-wide emissions target is cheaper with a carbon tax than with conventional regulations.*

A carbon tax would be reasonably easy to implement. Most carbon dioxide comes from fossil fuels, and the carbon tax could be applied when the fossil fuel is extracted from the ground, using the administrative infrastructure for existing taxes, such as excise taxes on coal and petroleum. The price of the tax would then follow the fuel through the market, where the end user would finally pay it. A tax credit would be generated if the carbon was used in such a way that it was not released into the atmosphere (such as production of plastic or capture of carbon in coal combustion followed by sequestration).

As part of a long-term policy, the carbon tax would start out relatively small and, over several decades, gradually increase until emissions have been reduced to the target level. Gases other than carbon dioxide, such as methane or nitrous oxide, would also be taxed but at a rate that takes into account how effective each one is at warming the planet. For example, 1 tonne of methane contributes approximately 32 times more warming than a tonne of carbon dioxide (Table 5.1), so the tax rate on methane would be proportionally higher than the tax rate on carbon dioxide.

The costs of reducing emissions would eventually be passed on to consumers. Thus, the net effect of a carbon tax is to raise the prices of goods and services by an amount proportional to the amount of the greenhouse gases released. Goods and services that are produced with no emission of greenhouse gases will not experience price increases, whereas the costs of goods and services that require the emission of significant amounts of greenhouse gases may see large price increases.

Many people automatically consider taxes to be bad, so they look at suggestions of a carbon tax with hostility. However, most economists argue that a well-designed tax serves a useful economic purpose. For activities that generate negative externalities (costs imposed on society, such as emitting greenhouse gases or smoking cigarettes), the free market prices these activities too low, leading to overconsumption of the associated good or service. Taxes on these activities correct for this and reduce consumption, which produces a socially beneficial outcome. Thus, an economist thinks of a carbon tax as fixing a problem in the free market. Unfortunately, in our present political environment, the prospects for implementing a carbon tax in the United States and in many other countries are dim.

12.3.2 Cap and Trade

An alternative way to put a price on greenhouse-gas emissions is a *cap-and-trade* system. Under cap and trade, the government issues a fixed number of permits each year, with each permit allowing the holder to emit a fixed amount (e.g., 1 tonne) of greenhouse gas to the

atmosphere. Emitters must hold permits for the amount of greenhouse gas they emit to the atmosphere. Thus, the total number of permits issued sets a cap on total emissions. Emitters with extra permits can sell them to those needing additional permits (hence the *trade* part). The price of the permits is set by the market, not by the government.

The economics of a cap-and-trade system is similar to that of a carbon tax. If the marginal cost of reducing 1 tonne of greenhouse gas emissions is less than the cost of the permit, the emitters will not emit that tonne. This allows them either to avoid having to buy a permit, or, if they already have a permit for this tonne, to sell it at a profit. If the marginal cost is more than the permit, the emitters will acquire a permit and emit that tonne. In the end, the emitters will reduce emissions until the marginal cost of reducing emissions equals the price of the permits. So if permits cost \$4 per tonne, Plant A will reduce emissions by 4 tonnes and Plant B will reduce emissions by 2 tonnes. This is the same result that was obtained for a carbon tax of \$4 per tonne.

In cap-and-trade systems, when a unit of greenhouse gas is emitted, a permit is retired. Therefore, the government must continually issue new permits to replace those that have been used. Over several decades, the number of permits issued each year will decrease following a prescribed schedule until the target emissions level is reached.

One of the most contentious issues in any cap-and-trade system is how the government issues those permits. One approach is for the government to auction the permits off. In that case, companies would buy the permits from the government and then pass the cost of the permits on to their customers through higher prices for their products. This approach has the advantage that permits go to those emitters who value the permits the most – and are therefore willing to pay the most. These will be the highest marginal cost emitters, for whom emissions reductions are most expensive.

Large emitters, like utilities that burn coal, oppose auctioning the permits because they would have to buy a lot of permits, the cost of which would then be passed on to consumers in the form of higher prices. This would reduce demand for their product – which would cost them money. An alternative is for the government to give away permits to companies for free. Because permits can be sold, this is equivalent to the government giving emitters money. Unsurprisingly, emitters favor this approach.

When giving the permits away for free, the decision about how to allocate permits is not determined by the market, but by other issues, such as fairness and political connections. For example, the imposition of a cap-and-trade system will be disruptive to industries that emit a lot of carbon to the atmosphere (e.g., coal companies). Giving these industries free permits is one way of providing financial aid to help them adjust to a new world in which emitting carbon to the atmosphere is no longer free. Politicians can also distribute permits to curry favor from particular constituents or to buy support for the policy from powerful sectors of society.

In the cap-and-trade bill considered by the US Congress in 2009 and 2010, for example, the majority of permits would initially be given away for free. Many of these free permits would go to large emitters, including coal companies. Because of that, these large emitters favored passage of the bill. The bill then required a slow transition to auctioning 100 percent of the permits over the next two decades.

One last issue is that both a carbon tax and a cap-and-trade system (with auctioned permits) would create an enormous transfer of wealth from consumers to the government. Thus, any policy to put a price on emissions must include some mechanism to recycle the payments into the economy. Many options have been discussed to do this. The money could be used to reduce the federal deficit or reduce other taxes, such as those on labor and capital. It could be used to help those with low incomes, who would be disproportionately hurt by the rise in energy prices. The government could also use the income for other beneficial activities, such as research and development of new energy technology. One frequently made suggestion is to rebate the money evenly to every citizen (sometimes referred to as “cap and dividend”).

12.3.3 Carbon Tax Versus Cap and Trade

Carbon tax and cap-and-trade systems are quite similar in many ways. Both reduce emissions by putting a price on emissions. Both systems allow companies to emit as much as they want, as long as they pay the tax or possess a permit for each unit emitted. In both cases, individual emitters reduce emissions until the marginal cost of reducing the next tonne of emissions is equal to the price on emissions. This moves emissions reductions to where they are cheapest, to the lowest marginal cost emitters, generating emissions reductions at the lowest cost.

Putting a price on emissions means that both approaches raise the price of fossil fuels and the goods and services made from them in proportion to the amount of greenhouse gases emitted by their consumption. Although consumers may not like to see prices go up, economics tells us it is the most efficient way to reach a socially optimum level of emissions, and it does so through several mechanisms. First, higher prices encourage consumers to reduce their consumption of greenhouse-gas-intensive goods and services. Second, putting a price on emissions encourages the economy to substitute climate-safe technology for their present technology. This occurs because these policies raise the prices of using fossil fuels, thereby increasing the competitiveness of climate-safe technologies (e.g., solar, wind, nuclear). Third, and most importantly, it encourages research on and development of new technologies that can replace today’s technologies that produce greenhouse gases. Humans are amazingly clever, and putting a price on emissions signals to the market that innovation and breakthrough technologies will pay off handsomely. With this market incentive, we can expect development of new technologies that dramatically reduce the cost of stabilizing the climate.

However, there are some important differences between a carbon tax and cap-and-trade system. Under a carbon tax, the policymakers set the tax rate, which in turn sets the cost to society of the emissions reductions. But it is not exactly known what the economy’s marginal cost of reduction is, so this means there is uncertainty in exactly how much of an emissions reduction will occur given a particular tax rate. Under a cap-and-trade system, in contrast, the policymakers set the total number of permits issued, and therefore the total emissions from the economy. However, the uncertainty in the marginal costs means that it is unknown how much it will cost to reach the specified level of emissions.

Here is a simple analogy. Imagine you go to a store to buy some soda. You are given \$50 and instructions to buy as much soda as you can. In that case, you know the total cost you will incur upfront (\$50), but you do not know how much soda this will purchase. This is analogous to a carbon tax. This creates the potential problem that the tax rate set by the government will not achieve the desired emissions reductions. However, the importance of this problem is frequently overstated. Because emissions reductions will take several decades to reach the desired level, the tax rate can be adjusted over time so that the desired emissions levels are eventually reached on schedule.

Now imagine that you go to the store and are given instructions to buy 12 cases of soda. In this case, you know exactly how much soda you will get (12 cases), but you do not know the cost. In the worst-case scenario, you might significantly underestimate the cost of a case of soda and not take enough money – and thereby be unable to get all 12 cases. This is the situation with a cap and trade. The total number of permits issued by the government sets the limit on emissions. However, the cost is uncertain. This creates a potential problem for cap-and-trade systems: Policymakers will issue too few permits (in an effort to bring emissions down sharply), and the cost of complying will be so high that significant economic disruption occurs. If this happens, the program might lose political support and be abandoned. Because of this risk, many cap-and-trade systems have tended to err on the side of caution and issue too many permits. In such a case, the price of the permits goes to zero, and little or no emissions reduction occurs.

To address the problem of runaway costs in a cap-and-trade system, some governments implement an escape valve. Should the cost of permits rise above a predetermined threshold, the government will sell more permits at that predetermined price. This would loosen the cap and increase emissions, but it would also reduce the cost to the economy. If, in contrast, the government issues too many permits (in an effort to keep costs down) and the price of permits drops below a predetermined floor, the government will commit to buying all permits being sold at that price, thus preventing the price of the permits from falling below that floor.

For political reasons, cap and trade has generally been the preferred climate policy for the last two decades. The European Union has a cap-and-trade system operating today. In the United States, however, opposition to government regulation has made cap and trade a toxic commodity, just like a carbon tax, and there seems to be little chance that one will be implemented at the federal level.

12.3.4 Offsets

Imagine that you own a power plant that emits 100 tonnes of carbon dioxide into the atmosphere every year. But you also own a forest, which absorbs 100 tonnes of carbon dioxide from the atmosphere each year. If a carbon tax is implemented, how much tax should you pay? Do you pay a tax on emissions (100 tonnes, from the power plant) or do you get credit for the carbon dioxide removed from the atmosphere by the forest? If you get full credit for the forest, then your net emissions are zero because the emissions from the plant are canceled by the uptake by the forest and you owe no carbon tax.

Actions that reduce the amount of carbon dioxide in the atmosphere – you can think of these as “negative emissions” – are often referred to as *offsets*. They are called offsets because, if credit is given to these negative emissions in a climate policy, emitters can use them to offset their greenhouse-gas emissions, thereby reducing their carbon tax.

From a physics standpoint, offsets *should* count as negative emissions. There is no difference to the climate system between not emitting 1 tonne of carbon dioxide and emitting 1 tonne while, at the same time, removing 1 tonne via an offsetting mechanism. Offsets also make sense from an efficiency standpoint, too. In much the same way that carbon tax and cap-and-trade systems are efficient because they encourage the lowest marginal cost emitters to make the reductions, offsets provide further flexibility in exactly how emissions are reduced. It may be cheaper, for example, for a coal-fired power plant to offset emissions by planting trees than it would be for it to capture the carbon produced in the coal combustion or pay the tax on the emissions. Because of this, offsets would be expected to lower the total cost of reaching any specified emissions target.

In reality, though, offsets are a dicey proposition. First, many offsets are difficult to verify. For example, measuring carbon uptake by a forest is an extremely complex problem. And what happens if the forest grows for several years, and then a forest fire burns it to the ground, releasing the sequestered carbon dioxide back to the atmosphere? How is this accounted for? Does the forest owner have to refund the credit he previously received for the offsets?

Then comes the question of *additionality*: Would the offsetting action have taken place without the additional value given to the offsetting action by the carbon emissions regime? To understand what I mean by this, consider the following example. You own a plot of land, so you go to a local power plant and offer to plant trees on it if they pay you. They do so, and in turn they use the carbon absorbed by the growing trees to offset some of their emissions, which reduces their carbon tax.

The problem arises because we do not know what would have happened without the payment from the power plant. If you would have planted those trees anyway, then the power plant should not use the removal of carbon from the atmosphere by the trees as offsets. In other words, in order for offsets to actually reduce carbon in the atmosphere, the offsetting action (in this case, planting of trees) must only have occurred because of the payment from the power plant.

This is referred to as additionality because, for an offset to count, we must be sure that the offsetting actions are *in addition* to what would have happened anyway and would not have occurred without the value that they have for climate change avoidance. Otherwise, the offsets achieve no environmental good. Mitigation programs that include offsets must therefore establish a mechanism to determine whether an offset satisfies additionality.

For these reasons, offsets are one of the most controversial aspects of any mitigation program. In fact, some of the biggest stumbling blocks in the negotiation of the Kyoto Protocol were the proposals to allow offsets from forests and agricultural lands to satisfy a major part (between one-quarter and one-half) of the total emissions reductions of each country. This proposal was pushed by the United States (a country with a lot of forest and farmland), but it was steadfastly opposed by some European countries.

12.4 Information and Voluntary Methods

A final way for governments to encourage emissions reductions is simply to give people information. If people can be convinced that climate change is a serious problem, and then provided information on ways to address the problem, they may take some action to address it without any further prompting by the government.

Information can indeed affect purchasing decisions. For example, car dealerships in the United States are required by law to put mileage stickers on cars they are selling. Although not every car buyer is concerned with mileage, many are, and this information helps them make the socially beneficial decision of buying a high-mileage car.

Information about whether a house is likely to flood as precipitation changes with warming can help developers build houses in climate-safe locations and, if they don't, help consumers avoid those houses. Another example of using information to motivate action is a greenhouse-gas registry. The requirement to simply report emissions can provide strong incentives for companies to reduce their emissions. Companies whose emissions far exceed those of their competitors will be embarrassed, whereas those with low emission may be viewed as socially responsible and thereby favored in the marketplace. In both cases, a registry will give companies incentive to reduce their emissions.

However, informational approaches have limits. In particular, these approaches generally do not compel people to make large or difficult changes. There is no guarantee, for example, that just informing the widget manufacturer in Section 12.1 that he could reduce his climate impact would get him to make the socially beneficial choice. That's particularly true if the widget market is extremely competitive. If he switches and other manufacturers do not, that could drive him out of business. Thus, there is little serious suggestion that we rely entirely on informational and voluntary approaches.

12.5 Putting the Approaches Together

To conclude this chapter, it is important to understand that the single most important policy for addressing climate change is:

Putting a price on emissions of greenhouse gases into the atmosphere

This could be done either through a carbon tax or a cap-and-trade system, and it is often referred to as putting a *price on carbon*, even though it must apply to all greenhouse gases. As Nobel Prize winning economist William Nordhaus says:

Whether someone is serious about tackling the global warming problem can be readily gauged by listening to what he or she says about the carbon price. Suppose you hear a public figure who speaks eloquently of the perils of global warming and proposes that the nation should move urgently to slow climate change. Suppose that person proposes regulating the fuel efficiency of cars, or requiring high-efficiency light bulbs, or subsidizing ethanol, or providing research support for solar power – but nowhere does the proposal raise the price of carbon. You should conclude

that the proposal is not really serious and does not recognize the central economic message about how to slow climate change. To a first approximation, raising the price of carbon is a necessary and sufficient step for tackling global warming. The rest is at best rhetoric and may actually be harmful in inducing economic inefficiencies.³

While putting a price on greenhouse-gas emissions should be the centerpiece of any policy, it may not be sufficient. Our recent experience has shown us that there are some economic sectors where progress with just a price on emissions will be slow. For these sectors, conventional regulations, such as efficiency standards or prohibitions of using particular technologies, can be implemented to reduce emissions. Examples of this would include fuel mileage standards for automobiles or restrictions on activities that are particularly unfriendly to the climate, such as the burning of coal.

Finally, information and voluntary policies can provide valuable additional incentives for public and private actors to reduce emissions. However, the large changes necessary for us to stabilize the climate are too big to be motivated entirely by voluntary policies. Thus, informational and voluntary approaches will almost certainly form *part* of our response to climate change but should not be relied upon for the bulk of emissions reductions.

12.6 Chapter Summary

- From an economic perspective, the climate problem arises because it is free to emit greenhouse gases into the atmosphere. The costs of the resulting climate impacts are paid by society, not the emitter. Therefore, the emitter has no incentive to reduce them. Economists call these costs imposed on society externalities.
- The central pillar of most serious mitigation policies is putting a price on emissions of greenhouse gases. There are two primary policies to do this: a carbon tax and a cap-and-trade system. These are frequently referred to as “market-based policies” because they do not tell anyone how much they can emit, just that they have to pay to dump greenhouse gases into the atmosphere.
- Under a carbon tax, emitters must pay a tax for each unit of greenhouse gas emitted. Under a cap-and-trade system, each emitter must hold government-issued permits equal to the amount of greenhouse gases emitted. The total number of permits sets the cap and emitters can trade any extra permits they possess.
- Over decades, the tax rate will rise or the number of permits issued will decrease following a predetermined schedule until emissions have ceased.
- Under these policies, emitters reduce emissions until the marginal cost (the cost of reducing the next unit) is equal to the carbon tax or the price of the permit. Because marginal costs vary among emitters, some emitters will make deeper cuts than others. These policies are efficient because they shift emissions reductions to where those reductions can be made most cheaply.

³ See Nordhaus (2008), p. 22.

- The net result of these policies is to (1) tilt the market towards climate-safe sources of energy, (2) encourage conservation of energy, and (3) encourage innovation of new climate-safe technologies.
- Offsets are processes that remove carbon from the atmosphere – they can be thought of as negative emissions. Whether these are allowed to offset real emissions is one of the most contentious parts of emissions-reduction policy debates. Offsets should satisfy additionality for them to count. This means that the offsetting activity would not have occurred without the additional value of the activity from its impact on emissions.
- Informational and voluntary approaches can be useful but are not sufficient to motivate the deep reduction in emissions required to stabilize the climate.

See www.andrewdessler.com/chapter12 for additional resources for this chapter.

TERMS

Additionality
Cap and trade
Carbon tax
Command-and-control regulation
Externality
Flexibility
Marginal cost
Market failure
Offsets
Price on carbon

PROBLEMS

1. Why do economists generally believe that the free market will not solve the climate problem by itself?
2. What is an externality?
3. (a) Explain how a carbon tax works.
(b) Explain how a cap-and-trade system works.
(c) What is the fundamental difference between these two policies?
(d) Given a carbon tax of x dollars (or a permit price of $\$x$), an emitter will reduce emissions until what criterion is satisfied?
4. Why are emissions reductions achieved by use of a carbon tax or cap-and-trade system cheaper than those achieved by use of conventional regulations?
5. (a) What is an offset?
(b) What does *additionality* mean?

6. In a *New York Times* op-ed piece (December 6, 2009), climate scientist Jim Hansen makes the following argument: “Consider the perverse effect cap and trade has on altruistic actions. Say you decide to buy a small, high-efficiency car. That reduces your emissions, but not your country’s. Instead it allows somebody else to buy a bigger SUV – because the total emissions are set by the cap.” He argues that this renders a cap-and-trade system ineffective. Why is this argument wrong?

7. Imagine a carbon tax is implemented. One day, you decide not to drive to the grocery store, and you apply for offset credit for the emissions that did not occur because this trip was not taken. Should you get paid for this? What would you have to prove in order to get paid?

8. For the following, assume that Plants A and B have the following marginal costs for reducing emissions:

Number of units reduced	Marginal costs for Plant A	Marginal costs for Plant B
1	\$3	\$1
2	\$5	\$2
3	\$7	\$3
4	\$9	\$5
5	\$11	\$9

(a) The government tells both plants to reduce three units of output. How much does this “conventional” regulation cost each plant? What is the total cost?

(b) The government implements a carbon tax of \$5 per unit. How much does each plant reduce? What is the total cost?

(c) Which approach is cheaper? Why is the cheaper approach cheaper?

9. The table below shows the marginal costs of two plants, each of which emits 10 units each year. They both have six permits, meaning that if they do not trade, they each would have to reduce 4 units. Assume that they are the only two actors in the market, so the prices are set by their marginal costs.

Number of units reduced	Marginal costs for Plant A	Marginal costs for Plant B
1	1	\$3
2	2	\$6
3	3	\$9
4	4	\$12
5	5	\$15
6	6	\$18
7	7	\$21

(a) How many permits will Plant B buy from Plant A?

(b) In what price range will these permits exchange hands?

10. Why will voluntary and informational approaches not lead to deep reductions in emissions?
11. For a closer-to-home example of a cap-and-trade system, imagine the following scenario: Your professor gives everyone five points of extra credit on the final exam. Further, the professor says that you can sell your extra credit to other students. What would you do? Sell yours, buy extra, or just hold on to your five points? More generally, which students will sell their extra credit and which will buy more?
12. When you buy an airline ticket, you can also buy a “carbon offset” that will cancel out the emissions from the flight. They typically do not provide much information about the carbon offset. Under what conditions would it be a good thing to buy? Would you buy one?
13. One argument made by those who oppose reducing emissions is, “The energy sources we use are always the cheapest and most plentiful – which are coal, oil, and natural gas. Wind, solar, etc. are more expensive and therefore bad for the economy.” What is right and what is wrong about this argument? For the purposes of this question, assume that the speaker is correct that the market price of renewable energy is higher than the market price of fossil fuels.
14. (a) Imagine a credit card whose bill was divided up and sent to everyone in the United States (i.e., if you purchased something on this card, every person in the United States would get a bill for $1/330,000,000$ of your total cost). Would the average person spend freely with this credit card? Or would they be as thrifty as they would if they had to pay the entire bill?
(b) Now imagine that every person in the United States has a credit card like this. What do you think is going to happen?
(c) How is this situation related to the climate change problem?
15. In this chapter, we talked about negative externalities. Can you think of an example of a positive externality?

In Chapters 11 and 12, we explored our options for addressing climate change. In Chapter 14, I will pull all these together so we can explore how we can choose among these options. Before we get to that discussion, though, I describe the context of the policy debate by providing a brief history of climate change science, policy, and politics.

13.1 The Beginning of Climate Science

People have been speculating on the nature of the climate for millennia, but modern climate science began in earnest in the early nineteenth century. In the 1820s, mathematician Joseph Fourier provided one of the first descriptions of the physics we now know as the greenhouse effect: A planet's atmosphere can trap heat and warm the surface of the planet beyond what it would be if it were a bare, airless rock (we covered this in Chapter 4).

The first recognition that the climate could change occurred in the 1830s, when geologist Louis Agassiz and other scientists identified glacial debris scattered across Europe. They correctly concluded that northern Europe must have previously been covered by ice. This was an unanticipated discovery; prior to that time, everyone had simply assumed that the climate they experienced was what it had always been and always would be. This discovery of widespread ice ages showed that climate had changed in the past, opening the possibility that it could change in the future. This motivated much of the scientific study of climate over the next century.

In 1856, an American scientist, Eunice Foote, conducted experiments and concluded that carbon dioxide could warm the climate. In 1859, physicist John Tyndall did more rigorous experiments and concluded that it was primarily water vapor and carbon dioxide in the atmosphere that absorbed infrared radiation, despite the fact that these two constituents make up just a small fraction of the atmosphere.

By the end of the nineteenth century, our knowledge of the climate system was advancing rapidly. In 1896, Svante Arrhenius, a Nobel Prize winner famous for his studies of the rates of chemical reactions, estimated the climate sensitivity – the warming of the planet from doubling the amount of carbon dioxide in the atmosphere (discussed in Chapter 6) – and estimated a value of 5 to 6°C. This is a bit higher than modern estimates of climate sensitivity of 2.5 to 4.0°C but still a remarkable achievement given how little we knew about the Earth at the time.

Although Arrhenius' calculations were primarily focused on explaining the ice ages, he also realized that humans were adding carbon dioxide to the atmosphere from coal

combustion. He estimated, however, that it would take thousands of years before humans would emit enough carbon dioxide to significantly warm the climate. However, he underestimated the rate of growth of emissions and therefore did not recognize that this would actually take only about a century.

The work of Arrhenius really marks the beginning of modern climate science. But while the bare outlines of the field were apparent at that time, many fundamental questions remained. Whereas Arrhenius had suggested that the carbon dioxide emitted by humans would accumulate in the atmosphere, many scientists thought that most of the carbon dioxide emitted by humans would be quickly absorbed by the oceans (as discussed in Chapter 5, that is true, but it's a slow process and, if emissions occur fast enough, carbon dioxide can build up in the atmosphere, as it is presently doing). Furthermore, some scientists suggested that water vapor so dominated the absorption of infrared radiation by the atmosphere that adding carbon dioxide to the atmosphere would have no effect on the greenhouse effect.

In addition, there was much less concern for environmental issues at that time. Nature was viewed as dangerous – in fairy tales, children who wandered into the woods did not come back. Indeed, the twists of weather and climate were among nature's cruellest weapons. When a tough winter or a severe drought could kill you, changing the climate does not seem like such a big deal.

So if the elements of human progress, such as the burning of fossil fuels, changed the climate, that was okay. Cutting down forest and replacing it with farmland or hunting predators like wolves to extinction were considered improvements. Nature was the enemy. Today, of course, we think differently about nature. We recognize that humans are strong enough to radically change our environment, and we therefore view the wilderness as something to be protected and conserved (although we do not always act that way). “Nature” is somewhere you may go on vacation, if you can find it and afford to travel there.

Temperatures rose during the first few decades of the twentieth century (see Figure 2.2), and by the 1930s it was apparent that the planet was warming. As *Time* magazine put it in 1939, “gaffers who claim that winters were harder when they were boys are quite right . . . weather men have no doubt that the world at least for the time being is growing warmer.”¹

Around this same time, Guy Stewart Callendar, an English inventor and engineer, suggested that this warming was caused by human emissions of carbon dioxide. This is likely the first time that someone suggested that human-induced climate change was underway. His work built off Arrhenius' observation that the burning of fossil fuels would warm the planet, but he revisited old measurements of atmospheric carbon dioxide and, unlike Arrhenius, realized that humans were already increasing the atmospheric levels of carbon dioxide. Like most other people of this time, however, Callendar was not terribly worried about any detrimental effects of human modification of the environment.

¹ Quoted in Weart (2008).

13.2 The Emergence of Environmentalism

By the 1950s, our view of the environment was changing as a result of several factors. One was the invention of nuclear weapons. Nuclear bombs with a yield of tens of kilotonnes had been used twice in World War II. By the 1950s, hydrogen-fusion bombs with yields 100 times larger had been developed. In fact, a single 1950s-era nuclear-armed bomber could carry more explosive power than all of the explosives used in World War II. It dawned on people that we humans now possessed the power to annihilate ourselves, making humanity a power in many ways comparable to nature.

Air pollution was also becoming an important issue. Probably the most famous air-pollution event in history was the *killer smog of London* in 1952. In London at that time, most homes were heated with coal, which dumped sooty smoke into the London air. In early December 1952, a temperature inversion over London created a stagnant air mass over the city. As people burned coal, dark soot accumulated above the city. This dark cloud hung over London, blocking out sunlight, which caused the temperature to plummet. This caused people to burn more coal for heat, leading to even more soot in the air.

During the height of the event on Sunday, December 7, the visibility in London was 1 foot. Cattle in the city's market were killed and their carcasses discarded rather than sold because their lungs were black. The particulates harmed people's health and killed many of the weak and old. On December 9, the weather changed, and the killer fog was blown away, vanishing as quickly as it had arrived – but not before several thousand Londoners had died.

At the same time, people in many parts of the world were getting richer. People who are poor tend to worry about where their next meal is coming from or where they are going to sleep that night – they are not terribly concerned with the environment. However, as people become richer and have disposable income to spend on less essential things, protecting the environment becomes a higher priority. Once you have money, you care about the air you breathe, where you are going to go camping this weekend, and the extinction of polar bears. As this happened, particularly in the United States and Europe, concern about the environment began growing.

This increasing interest in the environment was bolstered by the International Geophysical Year, which took place in 1957 and 1958. This was an international effort that coordinated pole-to-pole observations of the Earth in order to improve our understanding of the fundamental geophysical processes that govern the environment. This intensive year of observations greatly improved our understanding of the Earth – and of the myriad of ways that humans can alter it. One of the most famous measurements started during the International Geophysical Year was of atmospheric carbon dioxide, also known as the Keeling curve (plotted in Figure 5.1a). Within just a few years after commencement, these measurements showed that atmospheric carbon dioxide was rising as a result of human activities. Here was direct evidence of man's massive footprint on the planet.

13.2.1 The Tobacco Strategy

Around this same time, a seemingly unrelated debate was raging in our society over the health effects of smoking. By the early 1960s, it was clear that smoking cigarettes was bad for your health. In 1964, US Surgeon General Luther Terry released a scientific assessment entitled *Smoking and Health*,² which detailed some of the dire health consequences of smoking. The evidence supporting their conclusions was enormous – the report summarized nearly 7,000 scientific articles relating smoking and disease. The report made newspaper headlines across the country and was the lead story on television newscasts.

In response, the tobacco companies developed what has become colloquially known as the *tobacco strategy* – a concerted effort to cast doubt on established science in order to advance a particular policy goal. The goal of the tobacco strategy was to create doubt, as described in a tobacco company document from 1969:³

Doubt is our product since it is the best means of competing with the “body of fact” that exists in the mind of the general public. It is also the means of establishing a controversy.

They were not trying to prove that cigarettes were safe, as they themselves recognized that was impossible:

Doubt is also the limit of our “product”. Unfortunately, we cannot take a position directly opposing the anti-cigarette forces and say that cigarettes are a contributor to good health. No information that we have supports such a claim.

To push their agenda of doubt, the tobacco companies developed a set of actions to advance their strategy. This included:

- Find a small number of advocates with scientific credentials who would convey the message of doubt to the general public. They should appear to be independent of the corporations fighting the regulation, although of course they were not. Use these advocates to suggest that there is a vigorous debate in the scientific community.
- Cherry pick data and focus on a small number of unexplained or anomalous details (cherry picking was also discussed in Aside 2.1). Ignore the fact that the vast, vast, vast majority of data solidly support the consensus view.
- Create the impression of controversy simply by asking questions, even if the answers were known and did not support the corporations’ case.
- Under the guise of fairness, demand equal time from media outlets to present the corporations’ side.

Following this strategy, tobacco companies were able to keep the public debate over the health impacts of smoking alive for decades after it was settled in the scientific community.

² <https://profiles.nlm.nih.gov/spotlight/nn/catalog/nlm:nlmuid-101584932X202-doc>, accessed November 17, 2020.

³ A large number of tobacco company documents can be viewed on the Truth Tobacco Industry Documents (see www.industrydocuments.ucsf.edu/tobacco/). This particular document can be found at www.industrydocuments.ucsf.edu/tobacco/docs/#id=psdw0147, accessed November 17, 2020.

This episode would be just a sad historical footnote if not for the fact that the tobacco playbook has been used again and again to cast doubt on science in other public debates, including the science suggesting that humans are changing the climate.

13.3 The 1970s and 1980s: Ozone Depletion and Acid Rain

Environmentalism may have begun in the 1950s, but several events in the 1970s solidified it in the general public's consciousness. In the early 1970s, scientists first theorized that human-made halocarbons (frequently referred to as CFCs, which stand for *chlorofluorocarbons*) might deplete ozone. This threat was completely theoretical – it would be more than a decade before actual observations of ozone depletion were obtained – and there was no effective replacement for CFCs in many applications. Nevertheless, by the late 1970s, the United States banned CFCs from being used in some non-essential applications, such as a propellant in aerosol spray cans.

In response, CFC manufacturers and industries that used CFCs in their products joined together to defend the molecule. To do so, they took the techniques of the tobacco strategy – attack the science! – and derived a new version optimized for environmental issues. They focused on these main claims:

- We're not sure the harm is happening.
- If the harm is happening, we're not sure our molecule is to blame.

These points are straight from the tobacco debate. As in that debate, the goal of those defending CFCs was not to prove the molecule was safe, but to generate uncertainty and doubt sufficient to justify not regulating CFCs. Two new arguments were also added. The first is:

- If our molecule is to blame, then fixing the problem will be too expensive.

The goal is to scare people into believing that the solutions were worse than the problem, thereby slowing adoption of policies to regulate CFCs. This argument takes advantage of what psychologists call loss aversion – the fact that people are more worried about being made worse off than encouraged about being made better off. Thus, the possibility that environmental regulations could hurt the economy trumps in most people's minds the fact that they could also deliver large economic and social benefits.

A final new argument was a general attack on experts:

- Scientists advancing the harm are corrupt, biased, foolish, out to destroy capitalism, etc.

Science remains widely respected in our society, so it holds the high ground in policy debates. As a result, everybody wants to claim that science is on their side. But if the science is not on your side, then you want to deny the other side the ability to claim the science. By discrediting scientists, they are attempting to neutralize any advantage the scientific evidence provides the other side.

This is now a common argument in policy debates, and it has been terrible for the world. For example, as I write this in 2020, with the world stuck in middle of the coronavirus

pandemic, the delegitimization of science has led many people to doubt the experts that they should wear a mask, social distance, get vaccinated, etc. This has led to many avoidable deaths.

In fact, we should put our trust in science. The institution of science is one of the most successful endeavors in human history. The reason it works so well is the many checks in the process: Important conclusions about science are peer reviewed and then replicated in the crucible of science. The biases of any individual scientist are extremely unlikely to survive this, and our confidence in the most replicated studies – the Earth is warming, humans are to blame, etc. – should be quite high.

As the world grappled with ozone depletion, another environmental problem was emerging: acid rain. Many coal-fired power plants emit large amounts of sulfur dioxide and nitrogen oxides to the atmosphere. Once in the atmosphere, these molecules can be absorbed by cloud droplets and raindrops, and react with cloud water to form sulfuric acid and nitric acid. This is analogous to the way carbon dioxide dissolves into water to form carbonic acid (discussed in Chapter 5). When this acid rain falls to the ground, the types of potential damage it can do are numerous: leaching of nutrients from soils, acidification of lakes and rivers, damage to wildlife and plants, damage to human-built structures, and so on.

This entire theory of acid rain is scientifically quite simple, and research done over the 1970s and 1980s definitively connected emissions from power plants to the acidic precipitation. In response to this research, the first broad international agreement covering acid rain, The Convention on Long-Range Transboundary Air Pollution, was signed in Geneva by 34 member countries of the UN Economic Commission for Europe on November, 1979. The next year, the Council of the European Communities enacted a directive reducing sulfur dioxide emissions.

The Reagan Administration, however, was resistant to enacting regulations on emissions of acid rain precursors. To support their reticence, they turned to the tobacco playbook and focused on the uncertainties:

“The state of the science . . . probably will not yield a scientifically complete assessment of acid deposition in the next few years,” says the report prepared for Congress and the Reagan Administration. “To date, the state of the science will not allow assertive recommendations. Trends are weak and evasive. Data are spotty. One of the most basic uncertainties is the extent of damage caused by acid deposition and its rate of change.”⁴

Note that the US administration never contradicts the connection between power plant emissions and acid rain, they just say that there is uncertainty and we need to do more research. It is important to emphasize here that uncertainty *always* exists, so the mere existence of uncertainty doesn’t tell you anything about whether this is a serious problem or not.

The United States took no action on acid rain during the Reagan Administration. However, in the early 1990s, the George H. W. Bush Administration enacted regulations to reduce sulfur

⁴ “Acid Rain Facts Called Sketchy,” *The Globe and Mail* (Canada), June 12, 1984.

emissions through a cap-and-trade system – just like the cap-and-trade system discussed in Chapter 12. These regulations greatly reduced the emissions of sulfur at a price far below expectation. And, as expected, this greatly decreased the occurrence of acid rain. The success of cap and trade in helping solve the acid rain problem is one of the main reasons that policymakers looked hopefully at that mechanism for addressing climate change.

It is worth reiterating that the cap-and-trade solution in the United States to the acid rain problem emerged from the Republican George H. W. Bush Administration. At the time, it was viewed as a conservative-friendly method of solving the problem because it let the market determine how emissions reductions would be allocated. For this same reason, environmentalists were suspicious or outright opposed to cap and trade. Over time, and with the incredible success of the program, environmentalists came around to viewing cap and trade as a particularly effective way to solve environmental problems.

The ozone problem remained an active scientific and political issue throughout the early and mid-1980s. The original theories from the 1970s suggested that ozone depletion would be a slow process, taking half a century or longer for significant depletion of ozone to occur, and that it would primarily occur at mid-latitudes and high altitudes. But when scientists obtained the first evidence that ozone was actually being depleted as a result of CFCs, they found it was occurring much more rapidly and in an entirely different place. They observed extremely rapid loss of ozone over Antarctica, where every spring, roughly 90 percent of the ozone in the lower stratosphere was being destroyed in a month or so (it built back up during the rest of the year so that it was available to be destroyed again the following year). This annual loss of ozone became known as the *ozone hole*.

Within a few years, scientists discovered new chemical reactions involving chlorine derived from CFCs combined with the unique meteorology of the polar regions to be the cause of this rapid polar ozone depletion. This confirmed the role of humans and suggested that the problem might be more serious than had previously been recognized. In response to this threat, the countries of the world signed the *Montreal Protocol* in 1987, an international agreement committing the world to phasing out CFCs.

An important aspect of the Montreal Protocol was that the phase-out of CFCs happened in two stages. Industrialized countries phased out CFCs first, followed 10 years later by developing countries. There are several reasons for this. Industrialized countries are richer than the developing countries, so they have more resources to apply to phasing out CFCs. Moreover, by having the rich countries go first, economies of scale and technical advances would be expected to drive down the cost for developing countries of phasing out CFCs. There were also ethical considerations. The CFCs in the atmosphere – which were causing the ozone depletion – had mainly been released to the atmosphere by activities in the industrialized countries. Developing countries had contributed little to the problem. Thus, it was agreed that industrialized countries should take the first step to clean up the problem.

During and after the negotiation of the Montreal Protocol, the science of ozone depletion was advancing rapidly, and evidence continued to accrue about the dangers CFCs posed to the ozone layer. But even as the science became more certain, so-called ozone skeptics

stepped up their attacks on the science of ozone depletion. A good example is this 1989 quote from *National Review*:

The current situation can fairly be summarized as follows: The CFC-ozone theory is quite incomplete and cannot as yet be relied on to make predictions. The natural sources of stratospheric ozone have not yet been delineated, theoretically or experimentally. The Antarctic ozone hole is ephemeral; it comes and goes, and seems to be controlled by climatic factors outside of human control rather than by CFCs.

... A New York Times report of March 7, 1989 talks about the disadvantages of the CFC substitutes. They may be toxic, flammable, and corrosive; and they certainly won't work as well. They'll reduce the energy efficiency of appliances such as refrigerators, and they'll deteriorate, requiring frequent replacement. Nor is this all; about \$135 billion of equipment use CFCs in the United States alone, and much of this equipment will have to be replaced or modified to work well with the CFC substitutes. Eventually that will involve 100 million home refrigerators, the air-conditioners in 90 million cars, and the central air-conditioning plants in 100,000 large buildings. Good luck! The total costs haven't really been added up yet.⁵

If this argument sounds familiar, it once again is the tobacco strategy. And in retrospect, all of these arguments have turned out to be wrong. Two decades of research have concretely verified the link between CFCs and stratospheric ozone depletion. What is more, the costs of replacing CFCs with ozone-safe alternatives turned out to be so small that, when CFCs were completely phased out in the mid-1990s, virtually no one noticed.

13.4 The 1970s and 1980s: The Ascent of Free Markets

In the decades after World War II, one of the most important ideological debates was between the governing philosophies of capitalism and socialism. Over that same period, a related and parallel argument was brewing between economists arguing for free markets against those who argued for more government control of the economy. By the 1970s, though, both battles were turning into routs. Problems with socialism were becoming clear, and freeing markets from government control had worked well in a series of important test cases, such as letting markets set the exchange rate for national currencies.

In his inaugural address in 1981, Ronald Reagan declared the battle won: "Government is not the solution to our problem, government is the problem." Given that statement, it is unsurprising that his administration adopted a hostile view of government regulation. But this hostility to regulation created a problem: While much can be said for the strength and effectiveness of the free markets, we discussed in the last chapter why free markets cannot solve environmental problems, which are mainly caused by externalities. The incentive in a truly free market is for corporations to exploit externalities to increase profits, in this case to pollute without regard to the costs of pollution because those costs are paid by society.

⁵ S. F. Singer, "My Adventures in the Ozone Layer," *National Review*, June 1989.

Thus, solving environmental problems *requires* some limits on the markets in order to impose the costs of the externality on the polluters. This created a tension in the Reagan administration between adhering to their free-market principles and solving environmental problems. This was one of the primary factors that caused them to reject policies to reduce acid rain, as discussed in the previous section.

This hostility by the Reagan administration to environmental protection was an abrupt change in our politics. Prior to Reagan, environmental issues were non-partisan. Legislation that created the Environmental Protection Agency (EPA) was passed in 1970 with a 372–15 vote in the House of Representatives and a unanimous vote in the Senate. It was then signed by Republican President Richard Nixon. It would be unthinkable for Republicans to agree to those policies in 2020.

It is important to realize that Reagan's opposition to regulations was a guiding principle, not an absolute and irrevocable law. After all, the Reagan Administration did sign the Montreal Protocol that phased out ozone-depleting CFCs – something that would also be unthinkable for Republicans of 2020 to support.

This was not just a US development. In the late 1980s, around the world, those opposed to government control of society, including many who had just recently thrown off the yoke of the Soviet Union, opposed environmental regulations. They were motivated by the fundamental belief that these regulations, including on greenhouse-gas emissions, were an unacceptable infringement on freedom. This is nicely summed up by Vaclav Klaus, President of the Czech Republic (and one of the very few leaders of any country to doubt the mainstream view of the science of climate change): “The largest threat to freedom, democracy, the market economy, and prosperity at the end of the twentieth and at the beginning of the twenty-first century is no longer socialism. It is, instead, the ambitious, arrogant, unscrupulous ideology of environmentalism.”⁶

13.5 Climate Science in the 1970s

The Earth's temperature remained relatively constant between the 1940s and 1970s (Figure 2.2). Despite this, research in the 1950s, 1960s, and 1970s had emphasized the risk of global warming due to increasing abundances of atmospheric greenhouse gases. At the same time, however, the abundance of aerosols from human activities was also rising (e.g., from the burning of high-sulfur coal). As discussed in Chapter 6, aerosols tend to cool the planet, and this offsets some of the warming from increased greenhouse gases. Some scientists suggested that humans were in fact adding enough aerosols to the atmosphere to overpower greenhouse gases, and that the dominant human influence was a net cooling of the climate.

A legitimate scientific debate ensued over which effect would dominate, and by the end of the 1970s the debate had been settled in favor of those predicting that global warming would

⁶ V. Klaus, *Blue Planet in Green Shackles* (Washington, DC: Competitive Enterprise Institute, 2007).

be the dominant human influence. In recent years, some have misrepresented the existence of a debate to suggest that the scientific community in the 1970s was predicting global cooling. This is incorrect – there was never any widespread consensus among scientists that aerosol-induced cooling was the dominant influence of humans.⁷

The 1970s ended with the publication of an influential report⁸ from the US National Academy of Sciences that reviewed the science and came to this conclusion: “If carbon dioxide continues to increase, the study group finds no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible.” More research in the early 1980s fleshed out and confirmed the general view that humans were in the process of modifying the climate. However, the general public and most politicians were not yet focused on the issue.

13.6 The Year Everything Changed: 1988

1988 was the year when climate change went from being a mostly academic problem to a political one. The United States was in the middle of a blisteringly hot summer, with much of the country experiencing drought conditions and temperature records smashed on a seemingly daily basis. In August, a small number of US congressional leaders were interested in the problem of climate change, and they felt the time was right to hold a congressional hearing on it.

At that hearing, NASA climate scientist James Hansen declared that he was 99 percent confident that the world really was getting warmer and that there was a high degree of probability that it was due to human activities. Coming on the heels of the publicity over the ozone hole, this created a media firestorm, and it put the issue of climate change onto the political radar. In the next few months, the United Nations passed a resolution urging the “Protection of global climate for present and future generations of mankind.” *Time* magazine, instead of naming a “Person of the Year” for 1988, named “Endangered Earth” the “Planet of the Year.”

This was also the year that the Intergovernmental Panel on Climate Change, or IPCC, was formed (discussed in Chapter 1). During the negotiation of the Montreal Protocol, the World Meteorological Organization and the UN Environmental Programme had put out a series of scientific assessments on the science of stratospheric ozone depletion. These assessments were incredibly successful at establishing the bedrock scientific principles upon which the Montreal Protocol was negotiated. The climate policy community, seeing the success of

⁷ For a good review of the history of “global cooling” and how it is misrepresented in today’s debate, see Peterson, T. C. et al. (2008), “The myth of the 1970s global cooling scientific consensus,” *Bulletin of the American Meteorological Society* 89: 1325–1337.

⁸ Ad Hoc Study Group on Carbon Dioxide and Climate, *Carbon Dioxide and Climate: A Scientific Assessment* (Washington, DC: Climate Research Board, National Research Council, 1979).

these ozone assessments, concluded that similar assessments about climate science would help to facilitate those policy debates, and this was the job the IPCC was created to do.

As momentum for enacting regulations to reduce emissions began to grow, so did the pushback. Given that energy is a several trillion dollar per year business, it should come as little surprise that many people and institutions strenuously opposed regulations that would cost them some of these trillions. They were joined by those philosophically opposed to environmental regulations, including many in the Reagan Administration, as described in the Section 13.4.

With the tobacco strategy in mind, those opposed to regulations on greenhouse gases focused on attacking the science. To do this, they recruited a small group of contrarian scientists to make the public argument. Many of these so-called *climate skeptics* were veterans of previous battles – tobacco, acid rain, ozone – and they had deep experience in casting doubt. The skeptics’ views of science are heterogeneous; for example, some skeptics dispute that the Earth is warming, while others accept that the Earth is warming but dispute that humans are responsible. Some even dismiss the fundamental physics of the greenhouse effect. But they share an opposition for any science that might lead to increased government regulation.

In 1990, the IPCC put out its First Assessment Report on the science of climate change. In it, the IPCC concluded that “the size of this [observed] warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability.” This relatively weak statement about the role of humans in climate change reflected legitimate uncertainties in climate science at that time. Because of these uncertainties, a definitive attribution of the warming to greenhouse gases was not possible.

13.7 The Framework Convention on Climate Change: The First Climate Treaty

Despite the uncertainty reflected in the first IPCC report, many world leaders felt that action had to be taken on climate change. The result was the Earth Summit in Rio de Janeiro in 1992, from which emerged the treaty known as the *Framework Convention on Climate Change*, frequently referred to simply as the “Framework Convention” or by its initials, FCCC. The FCCC enjoys near-universal membership, with 192 countries having ratified it, including the United States, China, and all other big emitters. The principles enshrined in the FCCC remain the major building blocks on which negotiations of treaties to reduce emissions have been built.

The most contentious debate over climate change policies involves mitigation. In that regard, the stated goal of the FCCC is “to achieve stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system.” This statement receives widespread agreement at this level of abstraction. In practice, though, the meaning of this statement hinges on the

definition of the word *dangerous*. There is no scientific definition of what dangerous climate change is because this is a value judgment – climate change that one person may perceive as dangerous may not be perceived that way by someone else. It would be nearly 20 years before the world agreed on what dangerous was.

In order to bring fairness or *equity* to any climate change agreement, the FCCC also enshrines the concept of *common but differentiated responsibilities*. This means that all countries must participate in solving the climate change problem, but not necessarily the same way. For example, we might expect rich, industrialized countries to begin cutting their emissions first, with developing nations cutting their emissions later. The reasons for this are similar to the reasons that industrialized countries phased out CFCs first in the Montreal Protocol, followed later by developing countries. The industrialized countries are far richer than the developing countries, so they have more resources to apply to reducing emissions. Moreover, by having rich countries go first, economies of scale and technological advancement would bring down the cost of reducing emissions so by the time developing countries begin reducing their emissions, the cost to them would be less.

There are also moral considerations. The 2 billion or so poorest people in the world currently live hard lives of crushing poverty. One of the ways to raise these people out of poverty is through economic growth – increasing their consumption of goods and services. This requires energy, so anything that makes consuming energy harder or more expensive for the poorest will also make it harder to lift these people out of poverty. Common but differentiated responsibility is a way of saying that solutions to climate change should not work at cross-purposes to efforts to reduce poverty.

There is also the question of historical responsibility. Most of the increase in carbon dioxide in the atmosphere over the past 250 years is due to emissions from the industrialized countries. In fact, the world's rich countries are rich because of the energy they consumed – and the emissions that resulted. Thus, it makes sense for them to have a greater responsibility for taking the first steps toward cleaning up the problem. It is also clear, however, that developing countries must eventually contribute. China is now the largest emitter of carbon dioxide, and several other developing countries are either major emitters or on track to be. Reducing global emissions significantly over the coming century will be impossible without all countries eventually making deep emissions reductions.

The FCCC also included what is referred to as the *precautionary principle*: “Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures.” This is in direct contradiction to those who look at climate change and argue that we should wait until we understand the problem better before taking action. It is also widely (and perhaps intentionally) misunderstood. It does *not* say that, if the risks are high enough, we must take action. Rather, it says that scientific uncertainty should not be used as an excuse to do nothing. There may be many other reasons to do nothing (e.g., economic, moral), but uncertainty in the science should not be one.

The FCCC was intended to be a starting point for more specific and binding measures to be negotiated later. Consequently, in contrast to its ambitious principles and objectives, the treaty's concrete measures were weak. Under the FCCC, nations committed to reporting

their current and projected emissions and supporting climate research. Parties also accepted a general obligation to adopt and report progress on measures to limit emissions. Only for the industrialized countries did this general obligation also include the specific aim of returning emissions to 1990 levels by 2000. This target was non-binding, meaning that it was an aspirational target and there were no sanctions for missing the target.

13.8 The Kyoto Protocol

In 1995, the IPCC released its Second Assessment Report on the science of climate change, in which it concluded that “the balance of evidence suggests a discernible human influence on the climate.” This quote reflected the fact that the science of climate change had significantly advanced since the IPCC’s first assessment and there was now much more evidence linking the observed warming to human activities. But significant uncertainties remained.

Around that same time, it became clear that no country would achieve the emissions-reduction target set in the FCCC, and that a treaty with mandatory reductions would be required. In response to this development, the *Kyoto Protocol* was negotiated in December 1997. Unlike the FCCC’s non-binding goals, the Kyoto Protocol required emissions from participating industrialized countries, averaged over a commitment period running from 2008 through 2012, to be approximately 5 percent below their 1990 emissions level. Developing countries, however, had no requirement to reduce emissions.

The Protocol incorporated several provisions to allow flexibility in how nations met their emission limits. Flexibility mechanisms allow emissions reductions to be shifted to where they can be made most cheaply, thereby reducing the overall cost of attaining a particular emissions target. This is similar to how, in Chapter 12, I showed how a carbon tax shifts emissions reductions to the lowest marginal cost emitter, which is one reason the policy produces low-cost reductions.

Flexibility mechanisms in the Kyoto Protocol included targets being defined for total emissions of a basket of carbon dioxide and five other greenhouse gases (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride). Countries could meet their target by reducing emissions of some combination of these gases, so focusing emissions reductions on the gas that was cheapest to reduce would achieve their goal at lowest cost.

Emissions-reduction obligations could also be exchanged between nations through various mechanisms. Under one mechanism, known as the Clean Development Mechanism, industrialized countries could invest in emissions reduction projects where it is cheapest globally – typically in developing countries – and count those reductions toward their own goal. For example, France could invest in a wind farm in China and count the reduction in emissions toward France’s emissions target. Like offsets, such projects must satisfy additionality: It must be demonstrated that the wind farm in China would not have been built without the financial support of France through this program.

The Protocol also included provisions for nations to meet some of their obligation through offsets. The Protocol included credit for reforestation, but some countries, such as

the United States, wanted credit for other carbon-capturing activities, such as agriculture. This turned into a significant conflict at a negotiating session in November 2000 in The Hague. A proposed compromise was almost reached, but it was ultimately rejected at the last minute by the French and German environment ministers, who judged that the proposed offsets weakened the Kyoto commitments too much.

13.9 The George W. Bush Years: 2001–2009

Shortly after the breakdown in negotiations at the meeting in The Hague and just a few months after taking office in 2001, the Bush Administration announced it was withdrawing the United States from the Kyoto Protocol process. The reasons included too much scientific uncertainty about climate change and potential harm to the US economy – key arguments taken straight from the tobacco strategy.

A particular problem cited by the Bush Administration was the absence of emission limits for developing countries. Although “common but differentiated responsibilities” is enshrined in the FCCC – which George H. W. Bush signed – and had also been incorporated into the Montreal Protocol, the George W. Bush Administration painted this as unfair to the United States.

This tension between rich, industrialized countries and poorer, developing ones would be the defining disagreement in climate negotiations for the next decade. Rich countries wanted poorer countries to commit to emissions reductions, while poorer countries didn’t want to do anything to hamper their pursuit of economic growth, which would allow them to join the ranks of the rich.

Also in 2001, the IPCC released its Third Assessment Report on the science of climate change. The report came to this conclusion: “There is new and stronger evidence that most of the warming observed over the last 50 years is likely attributable to human activities.” Compared with the previous reports, this one made a much more definitive statement about the role of humans in the recent warming. However, there was still uncertainty, as reflected by the use of the word *likely*, which denotes a two out of three chance.

Despite the US withdrawal, enough countries ratified the Kyoto Protocol for it to enter into force on February 16, 2005. But the long delay awaiting the required ratifications meant that the Protocol entered into force only 3 years before the start of the 5-year commitment period (2008–2012). Some nations, such as members of the European Union, took aggressive action by enacting a large-scale cap-and-trade program, the European Trading System. But many other countries made little effort to achieve what would have been at that time a large deflection of emissions over very few years.

At the same time, in the absence of any federal efforts to reduce emissions in the United States, efforts trickled down to the state and local levels. For example, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont banded together to form the Regional

Greenhouse Gas Initiative, more commonly referred to by its initials, RGGI (and pronounced “reggie”).⁹ The RGGI is a regional cap-and-trade program that covers emissions from just one economic sector – electric power plants. The Western Climate Initiative was formed by a group of western states and Canadian provinces to also develop a regional cap-and-trade system. In addition, many individual US states and cities began planning efforts to reduce emissions.

In 2007, the IPCC released its Fourth Assessment Report on the science of climate change and came to this conclusion: “Most of the observed increase in globally averaged temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.” This continued the trend toward stronger statements implicating humans in the warming – the words *very likely* here denote 90 percent confidence.

With the end of the Kyoto Protocol in 2012 in sight, representatives of the world’s governments met in Bali in December 2007 to begin negotiations for a new climate treaty that would build on what the Kyoto Protocol had accomplished. Importantly, it was agreed in Bali that this new agreement would, unlike the Kyoto Protocol, include emissions reductions by both industrialized and developing countries. Subsequent negotiations quickly split over the relative efforts required of these two groups.

In 2008, as George W. Bush’s presidency was reaching its end, the campaign to succeed him heated up. Senator Barack Obama was the Democratic nominee, and he was opposed by the Republican nominee, Senator John McCain. Both candidates accepted the reality of climate change and the need to do something about it – in fact, Senator McCain had tried several times over the previous decade to get an emissions reduction bill through the US Senate. The disagreements between the candidates on climate policy were quite minor – e.g., arguments over how much we should rely on nuclear power to reduce emissions, how deep the cuts should be in 2050.

13.10 The Obama Years: 2009–2017

In December 2009, just 11 months after Barack Obama became President of the United States, an international meeting took place in Copenhagen to finalize the follow-on to the Kyoto Protocol. While hopes were raised by renewed US engagement under the Obama Administration, the Copenhagen meeting was marked by continuing disputes between developing and industrialized countries over sharing the burden of action. Developing nations wanted the industrialized world to make sharp, near-term (e.g., by 2020) reductions in emissions, whereas the industrialized world wanted the developing nations to agree to quantitative emissions reductions.

⁹ In May 2011, New Jersey announced its intention to cease participation in the program. In January 2020, it resumed participation.

On the final day of the conference, President Obama and a handful of key developing country leaders negotiated an agreement known as the *Copenhagen Accord*. It included these major points:

- Global temperatures should not rise more than 2°C beyond pre-industrial temperatures. This was a quantification of how much warming constituted “dangerous anthropogenic interference” in the FCCC.
- Deep cuts in emissions will be necessary. Recognizing equity issues, these deep cuts may be delayed in developing and poor countries.
- The world’s rich industrialized countries each agreed to set their own target for emissions in 2020. This was a departure from the previous approach of negotiating targets for each country that all other countries agreed to.
- The world’s developing countries agreed to take on mitigation efforts but did not accept specific emissions targets. China, for example, agreed to reduce greenhouse-gas intensity (the *T* term in the IPAT relation) by 40 to 45 percent below 2005 levels by 2020. However, given the rapid economic growth of China, this still meant that emissions would increase.

Around that same time, Obama and his congressional allies began advancing major bills on health care and climate change through Congress. In response to this, as well as general opposition to President Obama’s policies, the Tea Party, a libertarian wing of the Republican Party dedicated to reducing the role of government in our lives, became a major force in US politics. Because policies to reduce emissions require some government intervention in the energy market – usually by pricing carbon emissions either through a carbon tax or a cap-and-trade system – the Tea Party rabidly opposed climate legislation.

It should be noted that this marked another turning point in US politics. Just a few years before this, the Republican nominee for President (John McCain) supported a nearly identical plan to address climate change. In 2009, however, the opposition to regulations, begun as a general principle by Reagan, morphed into a near-religious opposition to any government action, including on climate change. This has become a defining aspect of policy arguments in 2020: During the coronavirus pandemic, this manifested as opposition of mask mandates and enforced social distancing that directly caused the deaths of many Americans.

The rise of the Tea Party put immense pressure on Republican politicians to reject any legislation to reduce emissions. Before 2009, a number of prominent Republicans openly acknowledged the risk of climate change and supported policies to reduce greenhouse-gas emissions. This included leaders in the party such as John McCain (2008 presidential nominee), Mitt Romney (2012 presidential nominee), and Newt Gingrich (former speaker of the house). After 2009, however, each of these politicians adopted a skeptical position on the science of climate change and opposed legislation to reduce emissions. Republican politicians who did not quickly find themselves out of a job.

In the 2010 US elections, Tea Party-affiliated candidates, virtually all of whom reject the science of climate change or the seriousness of the problem, were elected in numbers large enough to fundamentally change the composition of Congress. This ended any opportunity to get comprehensive climate legislation through the US Congress.

Conservative pushback on climate policy was also occurring in other countries. In Canada, the conservative government of Prime Minister Stephen Harper withdrew from the Kyoto Protocol in 2011. The government did this because of well-worn criticisms of the Protocol (e.g., it does not include developing countries) and because Canada has immense oil reserves in the form of tar sands, which will likely be worth significantly less if the world agrees to stringent emissions reductions. In 2013, a conservative government in Australia began rolling back a price on carbon emissions that had been implemented several years earlier by the previous government.

By the end of 2012, the end of the Kyoto Protocol's commitment period, most industrialized countries had not achieved their Kyoto Protocol targets. Those that did, mostly in Central and Eastern Europe, relied on the fact that the base year was 1990, prior to the collapse of the Soviet Union. After the dissolution of the Soviet Union in 1991, much of the inefficient industry there was shut down, leading to a huge decrease in emissions; despite subsequent growth, emissions there had not yet climbed back to 1990 levels by the time of the Kyoto Protocol's commitment period.

In 2012, Barack Obama was re-elected president, and he made climate change a key issue in his second term. Given the composition of Congress, though, getting any climate legislation through it was impossible. The Obama Administration instead focused on using existing authority granted to the administration under the US Clean Air Act to address climate change.

The most ambitious Obama policy was known as the Clean Power Plan. The plan required individual US states to set targets for emissions reductions. States would reduce emissions by improving efficiency (energy intensity) and switching away from high-carbon-intensity fuels like coal to lower-carbon-intensity fuels like natural gas, or climate-safe energy such as renewables. The Obama Administration also required better fuel economy – 54.5 miles per gallon for cars and light-duty trucks by model year 2025.

Around the same time, the IPCC released its Fifth Assessment Report. It concluded that “It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together.” This continues the trend towards strengthening the attribution statement – it now uses the words *extremely likely*, which denotes a 95 percent chance (compared to *very likely* (90 percent) in the Fourth Assessment and *likely* (66 percent) in the Third Assessment).

13.11 The Paris Agreement

The world again tried to come up with a global agreement to reduce emissions in Paris in 2015. The *Paris Agreement* required that nations propose their own climate actions and commitments, referred to as *Nationally Determined Contributions* (NDCs). By having each country propose its own target, the world avoided the problem of coming up with a target that everyone agreed on. That had been the basis of the Kyoto Protocol and had failed at the recent Copenhagen meeting because of long-running disagreements between rich, industrialized countries and poorer, developing ones.

The Paris Agreement also contained no penalty for a country missing its NDC. But transparency mechanisms would ensure that everyone would know how well all other countries are doing – sometimes called a “name and shame” system of enforcement. Overall, this approach may seem weak, but if states were willing to adopt more ambitious targets when the only consequence for missing their target was embarrassment, it was hoped that the approach might enable stronger aggregate action.

The first signs that this was correct came in the Intended NDCs submitted in 2015 when major industrialized countries stated emissions targets substantially stronger than their previous ones. The United States pledged to reduce emissions by 2025 by 26–28 percent below 2005 emissions. The European Union pledged to reduce emissions by 40 percent by 2030 compared to 1990 emissions.

Even more promising were strong statements from some developing and middle-income countries. Of particular note, China committed to reach its peak in carbon dioxide emissions by 2030, with emissions declining thereafter. This was a true shift in policy, as China had previously only talked about greenhouse-gas intensity reductions, not emissions reductions. They also committed to produce 20 percent of their energy in 2030 from renewable power sources. To do that will require them to build about 1 GW of renewable power every week for the next decade.

Because China is the de facto leader of the developing world, China’s agreement to limit emissions in the near term put enormous pressure on other developing countries to do the same. It put even more pressure on industrialized countries that were reluctant to reduce emissions. Over the years, the “China excuse” – that China was not reducing emissions – had become one of the most important arguments for those countries, and now that excuse was gone.

The other important part of the Paris Agreement was a new and more ambitious temperature target for the planet. The Paris Agreement aimed to limit warming to *well below* 2°C, while pursuing efforts to limit warming to 1.5°C (all temperatures are relative to the pre-industrial climate).

While the Paris Agreement should be viewed as a great success, it was never going to be the end of the effort to stabilize the climate. Emissions reductions committed to in the 2015 NDCs would limit warming in 2100 to 3–3.5°C – a significant reduction from temperature without the Paris Agreement of more than 4°C, but still far short of what’s necessary to stabilize temperature well below 2°C.

13.12 The Trump Years: 2017–2021

By the time Donald Trump took office as US President in 2017, the antipathy Republicans felt towards government regulation that began with Reagan and was turbocharged by the Tea Party continued as something closer to a religious edict. Because environmental problems often arise from externalities that the free market cannot solve, this generated intense partisanship over environmental regulations, which has become one of the defining divisions in modern US politics.

In fact, views on the environment have become a reliable proxy for political affiliation – if someone says that climate change is a hoax, you can be pretty sure they’re a Republican; if they say climate change is a serious problem, they’re a Democrat. It would be unimaginable for a Republican Presidential candidate in 2020 to acknowledge the seriousness of climate change or propose a serious policy to address it, both of which John McCain did when he was the Republican nominee in 2008. It would be equally unimaginable for a Democratic Presidential candidate to argue that the climate problem was a hoax.

It is therefore no surprise that, when Donald Trump took office in 2017, he immediately began undoing Obama’s climate policies. Among many actions to reduce environmental regulations, the Administration repealed Obama’s Clean Power Plan, rolled back the automobile fuel efficiency standards imposed by the Obama Administration, and revised the US government’s estimate of the social cost of carbon (discussed in Subsection 10.5.2).

Many of these actions were not just efforts to reduce regulation, but symbolic acts of hostility and disdain for efforts to address climate change. A good example is the withdrawal of the United States from the Paris Agreement. As discussed above, the targets in the Paris Agreement are entirely voluntary, and there is no penalty for missing the target. If the Trump Administration had wanted to maintain the appearance of taking climate change seriously, they could have simply revised the US target to something less ambitious and stayed in the agreement. But the Administration had no interest in the appearance of taking climate change seriously – on the contrary, the goal was to make it clear they did not take the problem seriously.

13.13 The Future: 2021 and Beyond

Despite US flip-flopping on climate, most of the rest of the world has been moving ahead. The Paris Agreement requires signatories to revise their NDCs every 5 years, and those revisions began to be submitted in 2020. They included announcements from China, Japan, South Korea, the European Union, and the United Kingdom that they would bring emissions down to *net zero* by 2050 or 2060. “Net zero” means that emissions will be drastically cut but may not reach zero. However, any remaining emissions will be canceled by carbon dioxide removal. Of particular importance was China’s commitment to go net zero by 2060 – given that, there’s really no excuse for any rich country to have a less ambitious target.

With Joe Biden’s ascension to the Presidency, the United States has once again seriously engaged in international negotiations over climate. One of the Biden Administration’s first acts was to rejoin the Paris Agreement. They also pledged the United States to achieve net zero emissions by mid-century.

This brings us up to date as of early 2021. In the next and last chapter of the book, we’ll talk about the future of climate policy and what actions we need to take to minimize the danger of climate change.

13.14 Chapter Summary

- Scientists have been studying climate change for nearly 200 years, and in that time a successful theory of climate has emerged. This theory was described in Chapters 1–7 of this book.
- The first prediction of human-induced climate change was made in 1896 by Svante Arrhenius. In the late 1930s, Guy Stewart Callendar made the first claim that human-induced global warming was actually occurring.
- In the 1950s, people realized that humans possessed the power to greatly modify our environment – and not to our benefit. And the economic growth and increases in wealth occurring at that time meant the environment had more value to people, and people had more money to spend to enjoy it.
- In the 1960s, tobacco companies pioneered efforts to cast doubt on science as a way to keep people smoking. This tobacco strategy is the basis of the strategy used by those trying to stall environmental regulation.
- In the 1970s and 1980s, the debates over ozone depletion and acid rain were a preview for the debate over climate. Those opposed to action on these problems refined the strategy of the tobacco companies of casting doubt on science and added arguments about costs of regulations, and attacks on the motivation and competence of the scientific establishment.
- The 1970s and 1980s also saw the emergence of the ideology of free markets. A strict adherence to free markets makes solving environmental problems like climate change, ozone depletion, or acid rain difficult because those problems are based on externalities. Solving those problems requires some government intervention in the market.
- The first climate treaty was the 1992 Framework Convention on Climate Change or FCCC. This treaty enshrined three important principles: (1) “common but differentiated responsibilities,” (2) the precautionary principle, and (3) an agreement that the world should limit greenhouse-gas emissions in order to prevent “dangerous” climate change.
- The 1997 Kyoto Protocol included binding reductions of emissions for industrialized countries – these countries had to reduce emissions during the commitment period (2008–2012) by an average of 5 percent below baseline (1990 emissions), with the exact amount varying by country. There were no restrictions placed on developing countries.
- At the 2009 Copenhagen meeting, the rift between rich, industrialized countries and poorer, developing countries prevented any global agreement on reducing emissions. The meeting did produce the Copenhagen Accord, which included an agreement that the world’s goal should be to avoid 2°C of warming above pre-industrial temperatures.
- Under the 2015 Paris Agreement, each country named their own emissions reduction target (known as NDCs). This approach avoids the problem of negotiating a global reductions emissions target. The Paris Agreement also strengthened the temperature target to well below 2°C, while pursuing efforts to limit warming to 1.5°C.
- The Paris Agreement NDCs put the world on a path for 3–3.5°C of warming. Clearly, additional reductions in emissions will be necessary to achieve the Paris Agreement’s temperature targets.

See www.andrewdessler.com/chapter13 for additional resources for this chapter.

TERMS

Chlorofluorocarbons, or CFCs
 Climate skeptics
 Common but differentiated responsibilities
 Copenhagen Accord
 Equity
 Framework Convention on Climate Change
 Killer smog of London
 Kyoto Protocol
 Montreal Protocol
 Nationally Determined Contributions (NDCs)
 Net zero
 Ozone hole
 Paris Agreement
 Precautionary principle
 Tobacco strategy

PROBLEMS

1. Your roommates have a party when you are out of town.
 - (a) When you return, the apartment is a mess, and they ask you to help clean it up. Do you help them?
 - (b) Under what conditions might you offer to help? What might they offer you to get you to help them?
 - (c) How is this situation analogous to the debate between developing and industrialized countries over mitigation efforts?
2. Donald Trump said that “The concept of global warming was created by and for the Chinese in order to make US manufacturing non-competitive.”¹⁰ Who was the first person to discover that climate could change? Who was the first person to predict that human emissions of carbon dioxide might warm the climate? Who first claimed that human-induced climate change was occurring? Is Trump correct?
3. Do an Internet search and find some websites skeptical of mainstream climate science. List three of the claims they make about the science of climate change. Given what we have covered in the first 12 chapters of this book, are these arguments convincing?
4. What are the three important principles enshrined in the Framework Convention on Climate Change?
5. What difference is there in how we view the environment today versus how people who lived in the nineteenth century viewed it? What are the factors that caused the change?

¹⁰ www.nytimes.com/2016/11/19/world/asia/china-trump-climate-change.html, accessed November 19, 2020.

6. Explain the precautionary principle. Can you think of an example in your life when you have applied the concept (or not applied it)?
7. (a) Explain the concept of equity as it was described in this chapter.
(b) How was it implemented in the Montreal Protocol?
(c) Explain how it was implemented in the Kyoto Protocol.
(d) How is it implemented in the Paris Agreement?
8. Under the Copenhagen Accord, China agreed to reduce its greenhouse-gas intensity by 45 percent in 2020 (relative to a base year of 2005).
(a) What annual growth rate gives you a 45 percent decrease over 15 years? (a decline is a negative growth rate)
(b) If affluence also grows at 7 percent/year and population grows at 1 percent/year (in addition to the change in greenhouse gas intensity), what would be the change in total emissions over the entire time period?

14

Putting It All Together: A Long-term Policy to Address Climate Change

We have now reached the final chapter on our trip through the problem of modern climate change. In the previous 13 chapters, we explored the fundamental physics that leads us to confidently conclude that humans are now changing the climate and that continuing to add greenhouse gases to the atmosphere could bring serious changes to our climate over the next century and beyond. We are not certain how bad this climate change will be, but the upper end of the range (global and annual average warming several degrees Celsius above pre-industrial temperatures) includes warming large enough for many to consider its impacts catastrophic. Even the lower end of the range, about 1.5°C – 2°C above pre-industrial temperatures, will be challenging for the world’s poorest as well as our most vulnerable ecosystems. We have also explored a number of possible responses to this risk, including mitigation, adaptation, solar radiation management, and carbon dioxide removal. We have even touched briefly on the political debate over climate change. In this chapter, I will discuss the elements of an effective response to climate change.

14.1 Decisions Under Uncertainty: Should We Reduce Emissions?

By this point in the book, you should recognize that the physics of the climate problem (covered in Chapters 3 and 4) is actually quite simple, and we can therefore have high confidence that humans are altering the climate. That does not mean we have perfect foresight, though. We don’t know how much greenhouse gases humans will emit, exactly how much warming will occur in response, especially at the regional level, nor do we know how expensive and difficult it will be to stabilize the climate.

The existence of such uncertainty in high-stakes policy decisions is not unusual. One might think that, in such a situation, it would be wise to wait until the uncertainty is reduced. But doing nothing is itself a choice with consequences. Given that carbon dioxide is accumulating in the atmosphere, every year waiting for new science to decrease uncertainty commits the planet to more eventual future warming and commits us to adapting to this additional warming.

What’s a better way to make decisions in the face of uncertainty? One way to think about this problem is to consider the following two arguments:

- Because the worst-case scenario of climate change is so serious, we must take action now to reduce emissions, even though we don’t know exactly how bad climate change will be.
- Because of the high cost of reducing emissions, we must be certain that climate change is serious before we take action.

Both statements argue that we must err on the side of caution in order to avoid a bad outcome. However, the bad outcome is different in these two arguments. In the first argument, the bad outcome is severe damage from unavoidable climate change, whereas in the second it is severe economic damage from responding too strenuously to climate change.

Which of these ways of framing the decision is correct? We can gain some insight into how to think about this by looking at some familiar examples of decisions in the face of uncertainty. First, consider a criminal trial. To convict someone of a crime, a jury must be convinced that the defendant is guilty beyond a reasonable doubt. The reason for this standard is that we, as a society, have decided that it is better to acquit a guilty person than convict an innocent one.

Put another way, there are two errors a jury can make. They can convict an innocent person, or they can acquit a guilty one. These errors are not equally bad – we judge that it is worse to convict an innocent person. So the standard of conviction (“guilty beyond a reasonable doubt”) is set to minimize the possibility of making the worse mistake. In so doing, we increase the chance that we make the other mistake, acquitting a guilty person.

Another example occurs in deliberations concerning national defense. For example, former Vice President Dick Cheney famously said, “If there’s a one-percent chance that Pakistani scientists are helping al Qaeda build or develop a nuclear weapon, we have to treat it as a certainty in terms of our response.”¹ As in our jury example, there are two errors here that we could make. We could respond as if al Qaeda had a nuclear weapon, but it turns out they do not have a nuclear weapon. Or we do not respond, and it turns out they do have one. In most deliberations about national defense, being unprepared for a threat is judged to be a far worse error than to respond to a threat that never materializes. That is the fundamental judgment that Cheney is making here.

So how do we think about climate change? Must we be certain beyond a reasonable doubt that climate change is a serious threat to mankind before taking action to reduce emissions? Or should we take action to reduce emissions even if there is just a 1 percent chance that it is a serious threat? This question boils down to your judgment of which error is worse: reducing emissions unnecessarily because climate change turns out to be a minor threat, or not reducing emissions and climate change turning out to be a serious threat.

Suppose that climate change turns out to be a minor problem. In that case, an aggressive mitigation program would impose costs as we rebuild our energy infrastructure from fossil fuels to renewables and other climate-safe energy sources. How bad would this be? Switching from fossil fuels to climate-safe energy has advantages completely unrelated to climate, such as reductions in air pollution. Moreover, because costs of transitioning to climate-safe energy would be spread over the next several decades, at least some of the cost can be avoided by scaling back future efforts once we learn they are unnecessary. Furthermore, fossil fuels will be exhausted in the next century or so. Thus, switching away from fossil fuels is inevitable and these costs are going to be paid eventually. It is hard to

¹ Quoted in R. Susskind, *The One Percent Doctrine: Deep Inside America’s Pursuit of Its Enemies Since 9/11* (New York: Simon & Schuster, 2006).

imagine a person living in year 2050 being upset that we switched from fossil fuels to climate-safe energy sources.

Now suppose that climate change turns out to follow the worst-case scenario. If we do nothing to reduce emissions, we doom the planet to much warmer temperatures for thousands of years. This could impose catastrophic costs on our society (both economic and moral). In this case, it is easy to imagine that a person living in the future would be furious that we did nothing to address a problem that we clearly saw coming.

In the end, it is difficult to make the argument that taking too much action on climate change is a worse error than taking too little. This would suggest a standard closer to Cheney's, that the risk of climate change justifies action to reduce emissions, even in the face of significant uncertainty.

Another factor that enters into decisions under uncertainty is irreversibility. If an action you take is irreversible, you have to be more certain that it is the right thing to do than for a decision that is easily reversible. That is why, for example, inmates on death row in the United States are allowed many appeals to their death sentence – executing someone is as irreversible an action as there is, so you want to be as sure as possible that you are executing the right person. Just putting someone in jail, in contrast, is reversible – if you realize later that you have made a mistake, you can simply release that person.

Reducing emissions is a reversible decision. If we decide later that climate change is not that serious, we can always change our policies and increase our consumption of fossil fuels. And the investments we make in alternative energy sources, such as solar and wind, are reversible over a few decades.

But the converse is not true. Once we emit carbon dioxide, it remains there for a very long time. You have committed the planet to millennia of higher temperatures or implementation of some form of geoengineering, either carbon dioxide removal or solar radiation management. And many of the impacts of climate change are also effectively irreversible, such as sea-level rise and loss of the Greenland or Antarctic ice sheets. Thus, the irreversibility of emitted carbon dioxide, its associated climate change, and climate impacts also tend to favor taking action to reduce emissions.

In the end, most people who have seriously looked at the problem, including almost every world government, have concluded that, despite the uncertainties, the world should be working to reduce emissions.

14.2 Picking a Long-term Goal

If we decide we want to take action to address climate change, then we need a long-term goal. Stabilizing the climate requires net emissions of greenhouse gases to eventually decline to zero, but how fast does that need to happen? The faster we cut emissions, the less climate change we will eventually experience, but the more difficult and expensive those cuts will be. This is the trade-off, and we want to pick a target that avoids the worst climate change but at a cost that is manageable and does not interfere with other policy goals, such as poverty reduction.

The Framework Convention on Climate Change gives us one hint – it says that we should cut emissions fast enough to avoid “dangerous” climate change. But what is *dangerous*? It is not a scientific term, so science cannot settle the issue. Rather, deciding what is dangerous requires value judgments, such as our views on risk, poverty, justice, environmental stewardship, government regulation, and many other contentious topics. There are various ways to determine a long-term goal, and I discuss two of them in this section.

14.2.1 Cost Versus Benefits

Cost–benefit analysis, as the name implies, is an examination of the costs and benefits of a proposed policy. In Subsection 12.3.1, I described how a company would respond if a price were put on emissions through a carbon tax or cap-and-trade system. Companies evaluate each tonne of emissions and choose whether emitting that tonne is cheaper than not emitting it. In the end, emitters choose actions that minimize their costs.

This idea of comparing costs and benefits became one of the primary drivers of public policy during the second half of the twentieth century. Today, in many countries, governmental policies are enacted only if it can be shown that benefits will exceed costs. Imagine, for example, that our economy can reduce emissions of greenhouse gases for a cost of \$5 billion, but we get \$10 billion of benefits by avoiding the climate impacts. We should certainly do it. On the other hand, if the costs were \$10 billion and the benefits \$5 billion, then the economist would recommend against this policy.

Such an approach sounds reasonable, and you might therefore wonder whether we can use this type of analysis to determine what our optimal climate policy is. The answer, as I’ll describe in this section, is probably not.

To estimate the net benefits of a particular climate policy, we need to evaluate two scenarios. The first is what’s known as the baseline scenario, where no climate policy is implemented, and therefore no climate change is avoided. In this baseline scenario, our economy incurs the costs of adaptation to the changing climate, as well as the impacts of climate change that cannot be adapted to.

This baseline scenario is then compared to a second scenario that includes a proposed mitigation policy (e.g., a carbon tax). Because of the mitigation in this policy, this alternate scenario has lower emissions and less climate change than the baseline. The total costs under the mitigation scenario are therefore the costs of adaptation and climate impacts, which are both lower than baseline because there is less climate change in this scenario, as well as the costs of reducing emissions.

If the costs under the baseline scenario are higher than under the mitigation scenario, then the policy generates a net benefit. Economists can use various techniques to investigate a large number of policies in order to find the one that delivers the largest benefit, which economists call the optimal climate policy.

In the abstract, cost–benefit analysis seems completely reasonable. However, performing this calculation and getting a quantitative answer is difficult. The first difficulty one encounters is estimating how much the climate will change under any particular scenarios. As discussed in

Chapter 9, it is not the average conditions that harm people, but the occurrence of extreme events – extreme temperature, extreme precipitation, extreme sea level – that drives much of the costs of climate change. Thus, predictions of the costs of climate change require predictions of these extreme events. And all of these predictions must be regionally specific, since extreme temperatures in a desert region, like the Southwest United States, have completely different implications for society than extreme temperatures for people living in the Arctic. We have some ability to make these predictions, but we must acknowledge considerable uncertainty in any regional projections of extremes.

In response to these changes in climate, people will adapt, and this adaptation also has costs. Unfortunately, we know little about how well and how quickly people adapt, or about what factors promote or constrain the capacity to adapt. Two extreme cases bound the range of assumptions that have been made about adaptation in projecting impacts. One extreme assumes that people will keep doing exactly what they are doing now, with no regard for the changed conditions. This approach, sometimes called the “dumb farmer” assumption, excludes any adaptation and so systematically overstates harms from climate change. The opposite extreme assumes perfect foresight and adaptation. Given our track record dealing with climate change, this assumption almost certainly understates the harms from climate change.

How well people will actually adapt to future climate changes is a wide-open question. Rich societies with well-functioning institutions are more able to adapt, and consequently much less vulnerable to climate change, than those without such advantages. However, having the capacity to adapt does not mean that effective adaptation will take place. There is ample evidence that we are not optimally adapted to our present climate. For example, we develop and maintain intensive agriculture in drought-prone regions, dependent on the unsustainable mining of groundwater. We also build in high-risk locations on low-lying coastlines, flood-prone river valleys, and fire- and slide-prone hillsides, and even rebuild repeatedly in the same locations after property is destroyed.

Adaptation will never be complete; and there will be costs of climate change that are not adapted to, and these costs must also be estimated. This was discussed in Subsection 10.5.1; the upshot was that estimating the costs of climate change is relatively easy for loss of goods and services that are sold on the open market (i.e., loss of real estate). For things like polar bears, however, for which a market value is harder to quantitatively establish, the cost of climate change estimated by different people can vary widely.

We also need to estimate the costs of mitigation – i.e., switching to renewable energy. We know how much renewable energy costs today, so we can estimate the cost of replacing fossil fuel energy using today’s costs. But we also know that the price of renewable energy has been dropping rapidly, so using today’s prices would almost certainly overstate the cost of mitigation. We therefore must incorporate some estimate of how fast prices of renewable energy will decline in the future. If we assume that rapid innovation and price drops continue, then the cost of reducing emissions will be much lower than if we do not make that assumption.

Another problem in estimating the costs of climate change comes from the timing of climate impacts. If a tonne of carbon is emitted into the atmosphere today, it will warm the

planet for centuries to come and will cause impacts over that entire time. But the cost of avoiding those impacts – by not emitting that tonne – must be paid today. To compare costs that are occurring at different times, we therefore need to convert the value of the climate impacts over the next few hundred years to its value to us today (i.e., its present value). This involves discounting, which we explored in detail in Section 10.4.

Although discounting is conceptually straightforward, the big uncertainty is what discount rate to use. Most analyses in the climate change policy debate use discount rates between 1 percent and 4 percent. The larger the discount rate, the lower the present value of future costs – and we will consequently be willing to pay less to avoid those impacts.

For example, with a discount rate of 1 percent, \$1 trillion of climate change damage in 100 years has a present value of \$370 billion. We should therefore be willing to pay up to \$370 billion dollars today to avoid it. In contrast, the Trump Administration advocated discount rates as high as 7 percent; at that rate, the \$1 trillion of climate change damage in 100 years has a present value of \$1 billion – meaning we would only be willing to pay \$1 billion to avoid those impacts. This difference in discount rates has an enormous impact on our estimates of costs and benefits.

Economic analysis suffers from another problem: It looks mainly at aggregate costs and benefits but not their distribution. As an example, consider two policy scenarios. In the first, the richest people on Earth gain \$2 billion, while the poorest lose \$1 billion. In the second, the poorest people on Earth gain \$1.5 billion, while the richest lose \$1 billion. Cost–benefit analysis would conclude that the first policy is best – it generates a net benefit to society of \$1 billion, which is larger than the net benefit of \$500 million generated by the second scenario. However, the distribution of the benefits also matters to many people – given the huge inequality in the world today, many people would view the second policy as being superior, even though it generates smaller net benefits.

This underscores a key problem with this type of analysis: While economics tells you what the most efficient solution is, it tells us nothing about whether the solution is fair or just. Adapting the Oscar Wilde quote, economics “knows the price of everything, but the value of nothing.” Fairness of a policy is a value judgment and different people looking at these policies may reach different conclusions about whether a policy is fair, and economic analysis provides no insight into who is right in such arguments.

A final problem with economic analysis comes from the problem of catastrophe, including worst-case outcomes such as abrupt climate changes, mass starvation, or even human extinction. Economic analyses struggle to assign a monetary value to a small and hard-to-quantify risk of truly terrible outcomes like these. As a result, most economic analyses ignore the worst-case scenario and focus on the most likely outcomes, effectively assigning a value of zero to potential catastrophe. This is a significant shortcoming: For some people, the mere possibility of an existential catastrophe in the next few centuries provides sufficient motivation for us to address climate change now.

Because of this, economics is limited in its ability to prescribe a quantitative response to climate change. Some economists advocate for deep, immediate cuts, while others call for more gradual ramping down of emissions over decades.

14.2.2 Target: 1.5°C and 2°C

Given all of the problems with economic analyses, is there a better way for us to determine our goal? A simpler way is to just choose a threshold in the climate system that we should avoid. The threshold should give us a good chance to avoid serious climate impacts, but it should be relaxed enough that it is politically and economically acceptable.

Beginning in the 1970s, those studying climate change began arguing that we should try to avoid warming greater than 2°C above pre-industrial temperatures. The first to say this was a Nobel Prize winning economist, William Nordhaus, who noted at the time that temperatures over the last few hundred thousand years had not exceeded this 2°C threshold. To me, a more important observation is that modern human society, with megacities and large-scale industrial food production, has developed over the past few hundred years during a period of relatively small climate variations – about 1°C. This stable climate provided the conditions (e.g., good weather for agriculture, robust freshwater supplies) under which human society flourished. Warming of more than 2°C, it is now clear, would move the world into a climate regime that would be new to modern human society.

This 2°C limit above pre-industrial temperatures became one of the most commonly articulated targets for climate policy. In the 2009 Copenhagen Accord, the world formally took note of this climate target. In the run up to the 2015 Paris meeting, however, it became increasingly clear that many serious impacts would arise if global average warming reached 2°C. The 2015 Paris Agreement therefore ultimately aimed at holding 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.”

It is important to remember that these targets are political compromises between diverse stakeholders. Countries that are particularly threatened by climate change would like more aggressive targets, while countries that produce fossil fuels support weaker targets. There is no scientific analysis that proves that 1.5°C or 2°C are magic limits, nor any reason to think that warming slightly below these thresholds is significantly better than warming slightly above. And we could just as easily have chosen a completely different metric, such as a limit in rate of warming (how many degrees per decade we were willing to accept) or a limit in atmospheric carbon dioxide. Some advocates, for example, argue that we should limit atmospheric carbon dioxide to 350 or 450 ppm. However, as of 2020, most climate policy discussion uses the Paris targets, and those targets have most of the momentum in policy discussions.

14.3 Limiting Warming to 1.5°C or 2°C

14.3.1 Carbon Budgets

When thinking about limiting warming, the focus must be on carbon dioxide. Other greenhouse gases matter, of course, but carbon dioxide is the most important because it remains in the atmosphere for so long (discussed in Chapter 5). Because of this, future

increases in radiative forcing will be mainly due to increases in that gas (Figure 8.3c). Thus, the key to avoiding large warming of the climate system is reducing carbon dioxide emissions as quickly as possible.

In Chapter 8, I showed you emissions scenarios based on different ways the world may evolve (Figure 8.4). In this section, we take a slightly different approach: We start with our targets (1.5°C or 2°C above pre-industrial temperatures) and calculate emissions trajectories consistent with them.

A useful way to think about these trajectories is in terms of a *carbon budget*. It turns out that the *peak warming* we eventually experience is determined by cumulative emissions of carbon dioxide. The scientific community's best estimate is that peak warming is $0.3\text{--}0.6^{\circ}\text{C}$ for every 1,000 GtCO₂ emitted to the atmosphere. Humans have already emitted about 2,200 GtCO₂ between the industrial revolution and the end of 2017, so we can stay under 2°C warming if we limit future emissions (after January 1, 2018) to 1,500 GtCO₂. This is a tight budget: With present-day emissions exceeding 40 GtCO₂ per year, we will blow through our remaining budget by the 2050s. To stay below 1.5°C is even more daunting. Our emissions budget for that limit is 580 GtCO₂, meaning that we are on track to exceed our budget for stabilizing below this temperature in the early 2030s.

Figure 14.1 shows a typical emissions scenario that maintains temperatures below the 1.5°C threshold at all times (the “ 1.5 no overshoot” lines). As I write this in 2020, achieving this trajectory requires rapid and deep reductions in emissions, starting very soon, with emissions declining ~ 50 percent below 2010 levels by 2030. The trajectory reaches net zero in the mid-2040s, and emissions are negative thereafter. Negative emissions mean that humans

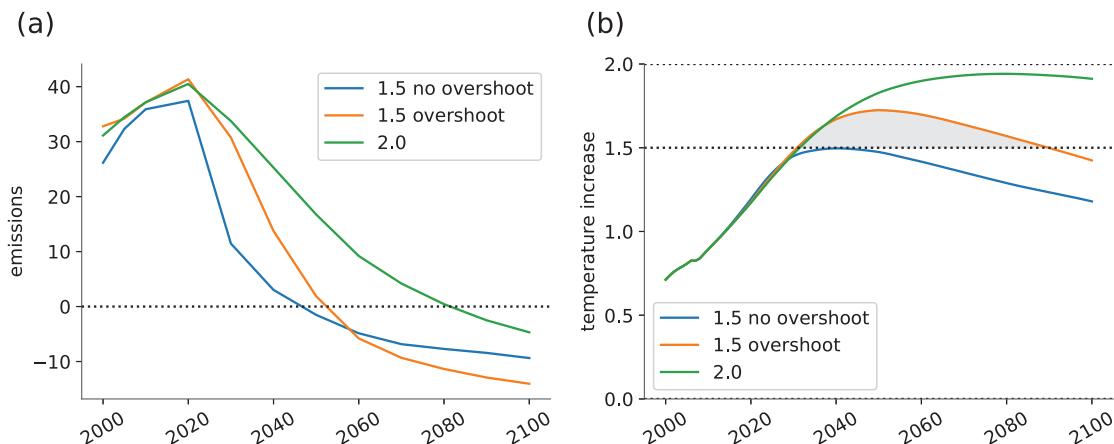


Figure 14.1 (a) Emissions scenarios for 1.5°C and 2°C . (b) Temperature trajectories associated with the scenarios. The values are averages from a large number of models. Downloaded from Daniel Huppmann et al., IAMC 1.5°C Scenario Explorer and Data hosted by IIASA, Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018, doi: 10.22022/SR15/08-2018.15429 | url: data.ene.iiasa.ac.at/iamc-1.5c-explorer (accessed July 27, 2020).

are removing more carbon dioxide from the atmosphere than they are adding. We talked about carbon dioxide removal in Section 11.4.

Figure 14.1 also shows an alternative 1.5°C trajectory (“1.5°C overshoot”), in which temperatures are allowed to exceed 1.5°C for a few decades before dropping back below 1.5°C. Allowing temperatures to exceed your threshold temporarily is known as an overshoot (the gray shaded region in Figure 14.1b; these were also discussed in Section 11.5). Having an overshoot means that emissions can drop more slowly than in a no-overshoot trajectory, which in turn means there is less near-term effort required. However, since the temperature is determined by total emissions, higher emissions early in the century means that you need larger negative emissions later in the century.

The negative emissions in the two 1.5°C trajectories imply the removal of hundreds of billions of tonnes of carbon dioxide from the atmosphere over a few decades. This is a herculean industrial task, to put it mildly, and our ability to accomplish this is entirely speculative. As an estimate of scale, think about how much infrastructure and money it takes for us to emit comparable amounts of carbon dioxide to the atmosphere – wells, mines, trains full of coal, pipelines, refineries, trucks, power plants. It seems likely that it’s going to take a comparable amount of infrastructure to pull this much carbon out of the atmosphere. Nevertheless, it is clear that achieving any 1.5°C target will require large negative emissions.²

Figure 14.1 also shows a trajectory for avoiding 2°C of warming (the “2.0” lines). This trajectory also shows emissions peaking in the early 2020s, then dropping ~50 percent below 2010 levels by about 2050, and reaching zero around 2080. Beyond that point, negative emissions are required. Clearly, limiting warming to 2°C is an easier task than keeping the warming below 1.5°C.

I should note that there is uncertainty in these 1.5°C and 2°C emissions trajectories. They were derived assuming a climate sensitivity in the middle of the range of possible values.³ If we are unlucky and the climate sensitivity is at the high end of the possible range, then we need to cut emissions even faster than shown in Figure 14.1a to achieve our targets; if we are lucky and climate sensitivity is on the low end, on the other hand, then we can stay below our temperature targets with weaker cuts. Overall, one should think of the trajectories in Figure 14.1a as giving us about a 50 percent chance of achieving a particular temperature goal.

14.3.2 What Is Required to Achieve These Emissions Trajectories?

If we convert the emissions trajectories in Figure 14.1a to rates of decline in emissions, we find that emissions need to drop around 8 percent per year during the 2020s to achieve the 1.5°C limit (with overshoot) and around 3 percent per year to achieve the 2°C limit.

² We could also try to stay below 1.5°C with solar radiation management, but unless coupled to carbon dioxide removal, the solar radiation management would have to be sustained indefinitely.

³ Climate sensitivity is a measure of how much warming you get in response to doubled carbon dioxide. Review Section 6.3 if you don’t remember this.

I noted in Chapter 8 how emissions can be thought of as the product of population, affluence, and technology (Equation 8.1: $I = P \times A \times T$; if you do not remember this, now is a good time to review Section 8.1). We also talked in Chapter 8 about how we expect the world's population to continue to increase in the future, and we also expect that people will continue to become richer. More quantitatively, we can expect the product of population times affluence ($P \times A$) to increase at 2 to 4 percent/year. This means that the technology term (i.e., the greenhouse-gas intensity) must decline by ~11 percent per year and ~6 percent per year in the 1.5°C and 2°C scenarios, respectively.

Again thinking back to Chapter 8, greenhouse-gas intensity is equal to the energy intensity times the carbon intensity (Equation 8.2). We expect energy intensity, a measure of how efficiently an economy uses energy, to continue to decrease by about 1–2 percent per year. Thus, the bulk of our emissions reduction comes from the carbon intensity term, which must decrease at 4 to 10 percent per year.

Decreasing the carbon intensity is often referred to as *decarbonizing* our energy system. Decarbonizing at 4–10 percent per year is an incredibly fast and challenging target. It is worth noting that this is the rate of emissions reduction as of 2019.⁴ Because climate change is controlled by the total emissions over time, the required rate of emissions reduction will get larger and more drastic for every year we delay emissions cuts. Had we started a transition away from fossil fuels a few decades ago, we could have decarbonized at a very slow rate. But we let corporations and politicians push the world to continue burning fossil fuels and stall political progress on reducing emissions. And we are now paying the price. It also explains why starting emissions reductions immediately is so important.

It is important to remember what decarbonizing means: Most of the energy used by humans is derived from fossil fuel combustion. To reduce emissions at the rates discussed in the last section, we have to replace this fossil fuel powered energy with climate-safe energy (renewables like solar and wind, nuclear, or fossil fuels with CCS).

Let's do a rough back-of-the-envelope calculation to see what will be required. Human society uses about 12 TW of power⁵. The infrastructure that produces and distributes this has a lifetime of about 50 years, meaning that about 2 percent (1/50) needs to be replaced every year. This corresponds to about 240 GW of power being retired every year – about 660 MW of power *every day*. For scale, a large coal-fired or nuclear power plant or a hydroelectric dam produces 1 GW of power.

Cutting carbon intensity by 4–10 percent per year means that we have to retire around 1 TW of fossil fuel power every year and replace it with climate-safe energy. This corresponds to building about 2 GW of climate-safe energy every day for the next

⁴ These numbers came from the United Nations Environment Programme (2019). Emissions Gap Report 2019. UNEP, Nairobi. Available online at www.unenvironment.org/resources/emissions-gap-report-2019.

⁵ This is final power, which does not include energy lost to waste heat and other inefficiencies that do not arise in an energy system dominated by electricity.

several decades. This will be an enormous challenge, and it is easy to conclude that the task is simply too big. But the power of human industrial society is also immense – it is, after all, big enough to change our global climate.

To see this more clearly, consider the following fact: human population increased by about 1 billion in the last 13 years (corresponding to a population increase of 200,000 people per day), and most of the population increase occurred in urban areas. This means that humans have been building the *equivalent of a city of 1 million people every 5 days for the last decade*. And this will continue for the next several decades, at least. If we can do that, then switching to carbon-free energy does not seem so daunting.

14.3.3 How Much Will This Cost?

As described in Chapter 12, the core component of any climate policy is a price on carbon. The price that emitters pay will increase the cost of fossil fuel energy, and this will ripple through the economy, increasing the cost of products made in proportion to how much fossil fuel energy was consumed in production.

In the public debate over climate policy, these higher costs are almost always cited as an argument against the proposed policy. Advocates opposed to action on climate claim that these higher costs for energy will destroy jobs, hurt families, bankrupt workers, and generally wreak havoc on our economy. But is that true?

Let's begin by deconstructing the overall framework of the argument. Advocates against pricing emissions base their argument on a false choice: We can do nothing to address climate change, which costs nothing, or we can implement a price on emissions, which will raise the cost of energy. If this were actually our choice, then obviously we would prefer the option that has zero cost.

But that's not the choice we face. As you saw in Chapter 9, the climate is already changing, and these changes are already costing us money. Thus, *we're already paying a climate tax*. And, as Chapter 8 detailed, you ain't seen nothin' yet: Future warming could be several times the warming we have already experienced, the costs of which would be staggering to our economy.

In addition to the cost of climate impacts, there are many other costs to using fossil fuels that we are also already paying. Air pollution from fossil fuel combustion kills millions of people worldwide every year, including tens of thousands of Americans. And other health impacts of fossil fuel extraction and combustion, from heart attacks to premature births to asthma attacks, just to name a few, cost society billions of dollars. Switching to renewable energy would reduce these economic costs and provide a large, immediate, and positive boost to our economy.

But there are even more hidden costs of fossil fuels. The price of oil is set by the worldwide market, so US foreign policy over the last half century has been focused on maintaining stability in the world oil market. This has led us, for example, into invading Iraq twice (1990 and 2003), starting wars that cost the United States trillions of dollars and hundreds of thousands of lives worldwide.

Despite our best efforts, however, we have not been able to maintain stability in the oil market. Oil price spikes associated with Middle East conflicts and oil embargos have frequently been followed by painful economic recessions. In the mid-2000s, for example, a spike in the price of oil was one of the contributing factors that led to the great recession of 2007–2009. In 2020, as I write this, the price of oil has dropped significantly because of the coronavirus pandemic combined with a price war between Russia and Saudi Arabia. This has laid waste to the US oil industry, bankrupted oil producers, and increased unemployment. The price of oil will inevitably rise again, bringing pain to other sectors of the economy. These kinds of economic disruptions do not occur with solar and wind energy – the price of the wind and the Sun is always zero – and this stability is another way that renewables provide large economic benefits.

Thus, there are extremely steep costs to the energy system we have now due to climate impacts and the many other of the consequences of fossil fuel energy. Switching to climate-safe energy may bring a short period – perhaps a decade or so – when the price of energy may rise in response to a price on emissions. This will occur right after the price on emissions is imposed, but before the utilities have had time to retire their fossil fuel assets and replace them with climate-safe energy sources that have no emissions and therefore pay nothing for emissions to the atmosphere.

During this period, the price on emissions will be an enormous revenue stream for the government. As discussed in Chapter 12, the government can use this revenue to ameliorate the damages of higher costs. If some segments of the population are hurt by the increase in the price of energy, then the government can help those segments manage the transition to renewable energy. This could include retraining workers (e.g., coal miners) or giving direct aid to help the poor adjust to higher prices on things like gasoline.

Over longer times, as the economy shifts to climate-safe energy, the money the government collects from emissions will go to zero because emissions have gone to zero. At that point, it has been estimated that the price of energy will be lower than we're paying today. Putting everything together, virtually every credible economic analysis concludes that our economy *will benefit* from the switch to renewables, although economists still debate some of the details, such as exactly how fast to switch.

Given this, you might wonder why anyone would oppose switching to renewable energy. The answer is in the distributions of costs and benefits. The benefits are distributed widely to society – everyone gets a small piece of it – but the costs of switching are focused in a small number of economic sectors that today make a ton of money extracting and burning fossil fuels, altering the climate, and killing people through air pollution. While most people would be better off switching to renewables, someone who owns a coal mine, for example, would be worse off.

In a perfect world, the fact that a few people are worse off would not stop policies that improve the lives of virtually everyone else. Unfortunately, that's not the world we live in. The people who stand to lose from switching, fossil fuel producers, are so politically powerful that politicians will help them maintain the status quo, even if it makes the majority of their constituents worse off.

Thus, when you hear someone say that we cannot afford to save the climate without destroying our economy, that person is either dreadfully misinformed or they are trying to protect a status quo in which a small number of fossil fuel producers make a huge amount of money to the detriment of people like you and me. What they're saying does not reflect any version of reality.

Many of these people, whom I call climate delayers because their goal is to slow down efforts to solve climate change, try to put the focus on "innovation" as the core component of climate policy. It is correct that innovation of new climate-safe technologies will absolutely help us in our quest to cheaply transition from a fossil fueled energy system to a climate-safe one. But the problem with putting innovation at the center of climate policy is that innovation is not a policy – you cannot pass a law or enact a regulation that says, "We will innovate." Rather, innovation is the result of policy. So if someone tells you that innovation is the key to solving the climate problem, ask them what specific policy they are proposing that will generate the required level of innovation.

There are many ways to enhance innovation. The government can directly fund research and development. But this is unlikely to be sufficient. What we really want is to provide an incentive for everyone in our economy to innovate. The way to do this is to put a price on carbon. Putting a price on emissions signals to the market that development of breakthrough technologies will pay off handsomely for whoever develops them. Experience with other environmental issues suggests that innovation is highly responsive to price incentives, so costs of environmental goals usually turn out lower than estimated in advance. For example, even without an explicit price on emissions, the cost of solar and wind has plummeted over the last decade because of research and development driven in large part by the expectation that a price on emissions will be imposed at some point in the future.

14.3.4 What Are the Elements of a Coherent Climate Policy?

First, we need a global price on greenhouse-gas emissions. However, there is no world government, so an appropriate policy needs to be simultaneously implemented in every country. This is crucial: If one or a few big emitters choose not to participate, then the countries that do participate will have to make larger and faster cuts in emissions. This is more expensive for the overall economy, and it is particularly expensive to those making the steep reductions. This leads to more economic pain for those participants, potentially eroding political support in those countries.

Second, although a price on carbon is crucial, it may be the case that a carbon price will not produce action fast enough to achieve our climate goals. In particular, there are some economic sectors where great progress can be made rapidly but where expected progress with just a price on carbon will be slow. For these sectors, conventional regulations and other incentives can be implemented to encourage careful energy use. One example is fuel mileage standards for automobiles. In addition, restrictions on activities that are particularly unfriendly to the climate, such as the burning of coal, might also be implemented.

Third, countries should fund the research and development of new technologies. Although it may be possible to solve the climate problem with existing technology, it is clear that new and improved technologies can ease the transition as well as reduce the cost. An example of transformative technology would be a breakthrough in battery energy storage. This would reduce the impact of the intermittency of renewable energy – e.g., solar energy generated during the day could be stored and then fed into the grid at night. Another example would be an “artificial leaf” that takes sunlight and uses it to split water into hydrogen and oxygen; the hydrogen could then be burned to produce energy.

Another area where we need research is in carbon dioxide removal. Almost all of the 1.5°C and 2°C trajectories rely on negative emissions late in the twenty-first century and beyond. A breakthrough technology that allowed removal of carbon dioxide from the atmosphere at low cost would be enormously helpful in achieving our climate goal.

Fourth, prepare to adapt to climate change. Regardless of what actions we take now, the globe will continue to warm for decades. And to the extent that this warming cannot be avoided, we must adapt to it. Thus, adaptation must necessarily be a part of our response to climate change. Anticipatory adaptation is cheapest, so we should begin to incorporate the reality of climate change into any plans for the future. This is particularly true for investments in long-lived infrastructure. When we build a road, airport, power plant, or anything else that we expect to last many decades, we must make sure that it is resilient to changes in the climate that might occur over that time. In addition, not every country has the resources to adapt, so mechanisms of providing international aid may have to be implemented.

Fifth, given how long we have waited to start taking climate change seriously, there is a real question of whether mitigation by itself is sufficient to avoid dangerous climate change (Section 11.5). In that case, solar radiation management may be our only way to avoid truly disastrous warming. We should prepare today for this by researching the various options in order to determine which are most likely to work and what the negative side effects might be.

Sixth, we must also realize that whatever policy we adopt now will probably not be exactly the right long-term policy. Because of this, both international agreements and the domestic policies that flow from them must be reviewed and amended as new information about the science of climate change and new technological developments arise.

In the end, we do not confidently know how hard it will be to reduce our emissions and make the transition to a fossil-fuel-free future. In this way, the climate change challenge is not unique; we almost never know in advance how much it will cost to comply with environmental regulations. Before regulations to reduce ozone depletion were passed in the 1980s, for example, some advocates predicted that the regulations would cause an economic apocalypse, with people in the developed world having to get rid of their air-conditioners, and millions in the developing world dying because of a lack of food refrigeration.

It turned out that innovation in response to the threat of regulation led to the development of substitutes for the ozone-depleting chemicals so cheap that, when the new, ozone-safe chemicals replaced the older ones, virtually no one noticed. The hope with climate change is that, once policies to reduce emissions are imposed, innovation by the private sector will produce breakthrough technologies that allow us to eliminate emissions cheaply and with minimal economic

disruption. We already see hints of that in the rapidly dropping costs of solar and wind energy over the last decade.

14.4 A Few Final Thoughts

If you have decided that climate change is something that we need to address, you may be wondering what you can do to help. There certainly are personal choices you can make that will reduce your share of emissions of greenhouse gases. Some of these choices will not only reduce emissions but also save you money and benefit you in other ways (e.g., take public transportation or walk instead of driving, eat less meat). Other choices may require upfront costs but will pay for themselves over time (e.g., add insulation to your attic or switch to LED lighting). Some choices may be difficult to justify on economic grounds alone (e.g., install photovoltaic solar panels on your house).

You should certainly undertake all of the voluntary individual actions that you can. Many of them will improve your life (e.g., eating less meat will make you healthier). But these individual actions are not going to lead to the changes necessary to solve the climate problem. That will require collective, coordinated action throughout the entire world. That is why the single most important thing you can do is become politically active – write letters to your representatives, participate in rallies, talk to your friends and neighbors, and vote for politicians who support action on climate.

In this book, I have tried to give a comprehensive overview of the climate change problem. Unlike what you might hear in the public debate, much of the science of climate change is extremely solid. There is no question that, when you add a greenhouse gas to the atmosphere, the planet will warm (Chapters 4 and 6). There is no question that human activities are increasing the amount of greenhouse gas in our atmosphere (Chapter 5). There is no question that the Earth is currently warming (Chapter 2), and it is warming about as much as you would expect from the addition of greenhouse gases (Chapter 7). This science is not new – much of it is a century or more old and has stood the test of time.

Other aspects of the problem are less certain. Quantitative projections of future climate change still contain significant uncertainty, much of that coming from uncertainties in which emissions scenario the world will follow (Chapter 8). Moreover, this uncertainty is magnified by uncertainty in how this warming will impact humans and those aspects of the environment that we care about. However, one conclusion is clear: If climate change falls toward the upper end of the predicted range, we will truly be remaking the face of the planet, and the results may be dire, perhaps even catastrophic (Chapter 9).

We know how to solve this problem (Chapters 11, 12, and 14), but we do not know how hard and expensive it will be – and we will not know until we try. Paralyzed by this uncertainty, the world has made little progress in solving this problem, despite decades of warnings from scientists (Chapter 13).

I do not know what the future holds. But I do know that, if we are going to navigate the coupled problems of energy and climate, we are going to need people like you to get involved

in all parts of the problem: the political, the economic, and the scientific. Given the enormous creativity and inventiveness of humans, there is no question that we *can* solve the problem. I encourage you to get involved to ensure that we do.

14.5 Chapter Summary

- When making decisions under uncertainty, one way to evaluate your choices is to identify the worse mistake and bias your decision away from that. In the climate debate, a strong argument can be made that not reacting strongly enough to climate change is worse than overreacting to it.
- The world's governments have agreed to limit warming to 1.5–2°C. This is not a scientific decision but a political one that balances diverse stakeholders and economic considerations. There is no reason to think that warming slightly above these thresholds is that much worse than warming slightly below.
- Limiting warming to 1.5°C above pre-industrial temperatures will require deep and immediate cuts in emissions, with net emissions going to zero by the middle of this century. Limiting warming to 2°C will also require immediate cuts, but they need not be as steep, and emissions need to reach net zero later in the century.
- Both the 1.5°C and 2°C emissions trajectories require large negative emissions later in the century. Our ability to pull enough carbon dioxide out of the atmosphere at reasonable cost is entirely speculative.
- Limiting warming to 1.5°C or 2°C will require building a few GW of renewable energy every day for the next few decades. This sounds like a lot – and it is – but human industrial capacity is immense, and this is entirely achievable, if we decide to do it.
- Some advocates will argue that switching to renewables will kill the economy. This is incorrect – large externalities make fossil fuels more expensive than renewables. Switching to renewables will actually improve the economy.

See www.andrewdessler.com/chapter14 for additional resources for this chapter.

TERMS

Carbon budget
Decarbonize

PROBLEMS

1. What is the single most important thing the world needs to do to address climate change? Why?

2. A friend argues, “We must be certain climate change is a problem before we take action.” Another friend argues, “We must take action if the slightest chance exists that climate change could be catastrophic.” How do you determine which one is right? Which one (if either) do you judge to be correct?
3. How does irreversibility of the choices affect policy decisions?
4. Imagine that your hometown is always at risk of being destroyed by some natural disaster (tornado, hurricane, earthquake). How much would you pay each year to eliminate the chance that the disaster would occur in that year? What are some ways you could determine this value?
5. (a) Explain conceptually the role that discounting plays in determining climate change policy.
(b) If you change the discount rate from 0 percent to 4 percent, how will this change your policy?
6. Juries in criminal trials are given a standard of evidence that must be crossed in order to find a defendant guilty. What is it? What would the standard be if our society decided that the worse error is to acquit a guilty person?
7. For climate impacts happening in 50 years, how much effort do you think we should make to eliminate those? What about impacts happening in 500 years?
8. Economic analyses struggle to assign a monetary value to a small chance of a truly terrible outcome. To see this, imagine that some otherwise unavoidable activity carries with it a one-in-a-thousand chance of killing you. How much money would you spend to avoid that activity? What if the risk of death were 1 percent or 10 percent?

Solutions to Selected Quantitative Problems

Chapter 1

1. White House: 38.90°N , 77.04°W ; Kremlin: 55.75°N , 37.62°E ; Pyramids: 29.98°N , 31.13°E
2. (b) 302, 212, 158, 122, 32, 14°F
3. (b) 0.56°C
4. -40
8. (a) 7 percent and 4 percent
(b) 31°C and 33°C , it increased by 2°C over this period

Chapter 2

1. (a) Total growth is $3.5''$. (b) $0.7''/\text{year}$
(c) You cannot determine his absolute height from the information given.
2. From 1880 to 2020, the Earth warmed $1.1^{\circ}\text{C} = 2^{\circ}\text{F}$. From 1970 to 2020, the Earth warmed $0.9^{\circ}\text{C} = 1.6^{\circ}\text{F}$.
11. No

Chapter 3

1. A 1-K temperature increase is equal to a 1.8°F or 1°C temperature increase.
5. Power radiated by the Sun is equal to $4\pi r^2\sigma T^4 = 4\pi(700,000 \times 10^3 \text{ m})^2 (5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4) (6,000 \text{ K})^4 = 4.5 \times 10^{26} \text{ W}$
7. Total energy = $60 \text{ J/s} (7 \times 86,400 \text{ s}) = 36 \text{ million J}$
11. It is not correct. An unchanging bank balance means that money deposited equals money withdrawn; it does not mean that no money was deposited or withdrawn.
12. (a) The total heat capacity = $4.18 \text{ J/g/K} \times 200 \text{ g} = 836 \text{ J/K}$. The warming rate = $150 \text{ J/s}/(836 \text{ J/K}) = 0.18 \text{ K/s}$.
(b) The amount of warming needed to reach boiling from room temperature is $100^{\circ}\text{C} - 22^{\circ}\text{C} = 78^{\circ}\text{C} = 78 \text{ K}$. The time required for this is $78 \text{ K}/(0.18 \text{ K/s}) = 434 \text{ s}$.

Chapter 4

2. (a) Total power output by the star = $4\pi r^2 S = 4\pi(100 \times 10^6 \times 10^3 \text{ m})^2(2,000 \text{ W/m}^2) = 2.5 \times 10^{26} \text{ W}$.
(b) The solar constant scales as $1/r^2$, so the solar constant for this planet is $2,000 \text{ W/m}^2 (100^2)/(75^2) = 3,555 \text{ W/m}^2$.

3. $T = 278 \text{ K}$
8. $T = 266 \text{ K}$
11. About 0.01
15. The solar constant increases to $5,440 \text{ W/m}^2$ and the Earth's temperature will increase from 288 K to 403 K .
19. (a) $375,000 \text{ km}^2$
(b) 0.07 percent

Chapter 5

2. Carbon dioxide exhaled by humans, animals, etc. is part of the fast cycle between the land biosphere and the atmosphere. Over long periods, the cycle is in balance and leads to no net increase in atmospheric carbon dioxide. Carbon from fossil fuels, on the other hand, was safely sequestered in the rocks and would not have been released to the atmosphere for many millions or even billions of years. This does lead to a net increase in atmospheric carbon dioxide.

4. Carbon from the biosphere has low amounts of carbon-13, but (relatively) large amounts of carbon-14. Carbon from a volcano has large amounts of carbon-13 and low amounts of carbon-14. Carbon from fossil fuels has low amounts of carbon-13 and low amounts of carbon-14. Analysis of the carbon added to the atmosphere shows that its isotopic composition matches fossil fuels.

5. Humans are adding carbon to the atmosphere by extracting and burning fossil fuels and by land-use changes.

Chapter 6

1. 5.7 W/m^2
3. (b) 0.27 K per W/m^2
(c) 0.32 K per W/m^2
6. -3.4 W/m^2
9. An increase in albedo from 0.30 to 0.312
13. The change in albedo will change the planet's temperature more.
15. About 0.8 K

Chapter 7

3. Feedbacks react to initial changes in surface temperature and amplify or ameliorate them. Feedbacks cannot be the ultimate cause of climate change.
4. The ice ages begin with a small perturbation to temperature caused by changes in the Earth's orbit. These small temperature changes are amplified by a carbon dioxide feedback: as the planet warms, carbon dioxide is released into the atmosphere, providing further warming. Because carbon is acting like a feedback, it lags the temperature change.

Chapter 8

2. $I = \text{CO}_2 \text{ emissions}$ (CO_2 emitted), $P = \text{population}$ (number of people), $A = \text{affluence}$ (\$/person), $T = \text{greenhouse-gas intensity}$ (CO_2 emitted/\$)
3. (a) Energy intensity (J/\$) and carbon intensity (CO_2 emitted/J)
(b) Carbon intensity decreases
(c) Energy intensity decreases
(d) Carbon intensity increases.
6. (a) T must decrease at about 5 percent per year
(b) T must decrease at about 6 percent per year.

Chapter 10

1. (a) \$117
(b) Seven doubling periods
(c) \$128
4. Present value of \$1 trillion in 50 years at 1, 2, 4, 6, and 8 percent discount rate is \$608 billion, \$372 billion, \$141 billion, \$54 billion, and \$21 billion, respectively. In all except the highest discount rate, you'd rather spend money to reduce emissions than deal with the impacts of climate change.
6. (a) 7.5 percent
(b) Take the lump sum.
10. 5 minutes (the depth is 10 ft after 1 minute, 20 ft after 2 minutes, 40 ft after 3 minutes, 80 ft after 4 minutes, and 160 ft after 5 minutes)
13. 68.7 days

Chapter 12

8. (a) Plant A = $\$3 + 5 + 7 = \15 ; Plant B = $\$1 + 2 + 3 = \6 ; total = $\$21$
(b) Plant A reduces 2 units, Plant B reduces 4 units; total cost = $\$3 + 5$ for Plant A + $\$1 + 2 + 3 + 5$ for Plant B, for a total of $\$19$.
(c) The carbon tax is cheaper because the carbon tax shifts reductions to Plant A, the lowest marginal cost emitter (i.e., where emissions cuts are cheapest).

Chapter 13

8. (a) $0.55 = (1 + x/100)^{15}$; solve for $x = -3.9\%/\text{year}$
(b) Total growth rate = $7\% + 1\% - 3.9\% = 4.1\%/\text{year}$; $(1.041)^{15} = 1.8$; so emissions would increase by about 80 percent over this period, even though greenhouse-gas intensity was declining.

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