CLIMATE CHANGE

THE SCIENCE OF GLOBAL WARMING AND OUR ENERGY FUTURE

SECOND EDITION

EDMOND A. MATHEZ AND JASON E. SMERDON

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To our children, Sophia and Lucas, and Anaïs and Emile, and to all the others of their generation who will bear many of the burdens of climate change and who will ultimately be tasked with finding a path to a more sustainable future.

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PREFACE

The genesis of the first edition of *Climate Change: The Science of Global Warming and Our Energy Future* was a document to support the development of the American Museum of Natural History's special exhibition *Climate Change: Threat to Life and Our Energy Future*, which opened in New York City in October 2008 and for which one of us (EAM) served as co-curator. Thus the original book was highly generalized, written, as it was, for a relatively broad audience. Since the time of writing the first edition and through our continued classroom experiences, however, it became apparent that university students need a more substantial introduction to climate science. Thus was born this second edition, which is much expanded from the first. Its target audiences include undergraduate students in beginning to upper-division climate courses, as well as graduate students in nontechnical programs such as education, journalism, and environmental policy. We seek to appeal to this wide university audience with a conceptual focus on the subject matter, avoiding complex mathematical formulations and layering content by consigning detailed or focused arguments to boxes. We hope that this approach will provide instructors with a basis for more in-depth classroom investigation.

This edition also takes on a somewhat more didactic character than the first. Each chapter ends with a roundup called "Key Points in This Chapter," in which the chapter's salient points are listed. Most chapters also contain a section titled "Back-of-the-Envelope Calculation," in which a simple computation illustrates one of the relevant chapter principles. Each "Historical Note" presents a biographical sketch of a scientist central to the development of climate science, providing the historical context of our present knowledge. Readers should also understand that this book relies mainly on the primary scientific literature. We nevertheless have limited the citations on each subject to a relatively few recent references, the intent being to provide a bibliography that allows the student practical entry into the broader literature. We must emphasize, however, that the narrative is based on an enormous body of work involving thousands of people, not all of whose work is cited. Finally, similar to the first edition, this second edition is a narrative account, written more as a story than in the style of a traditional textbook.

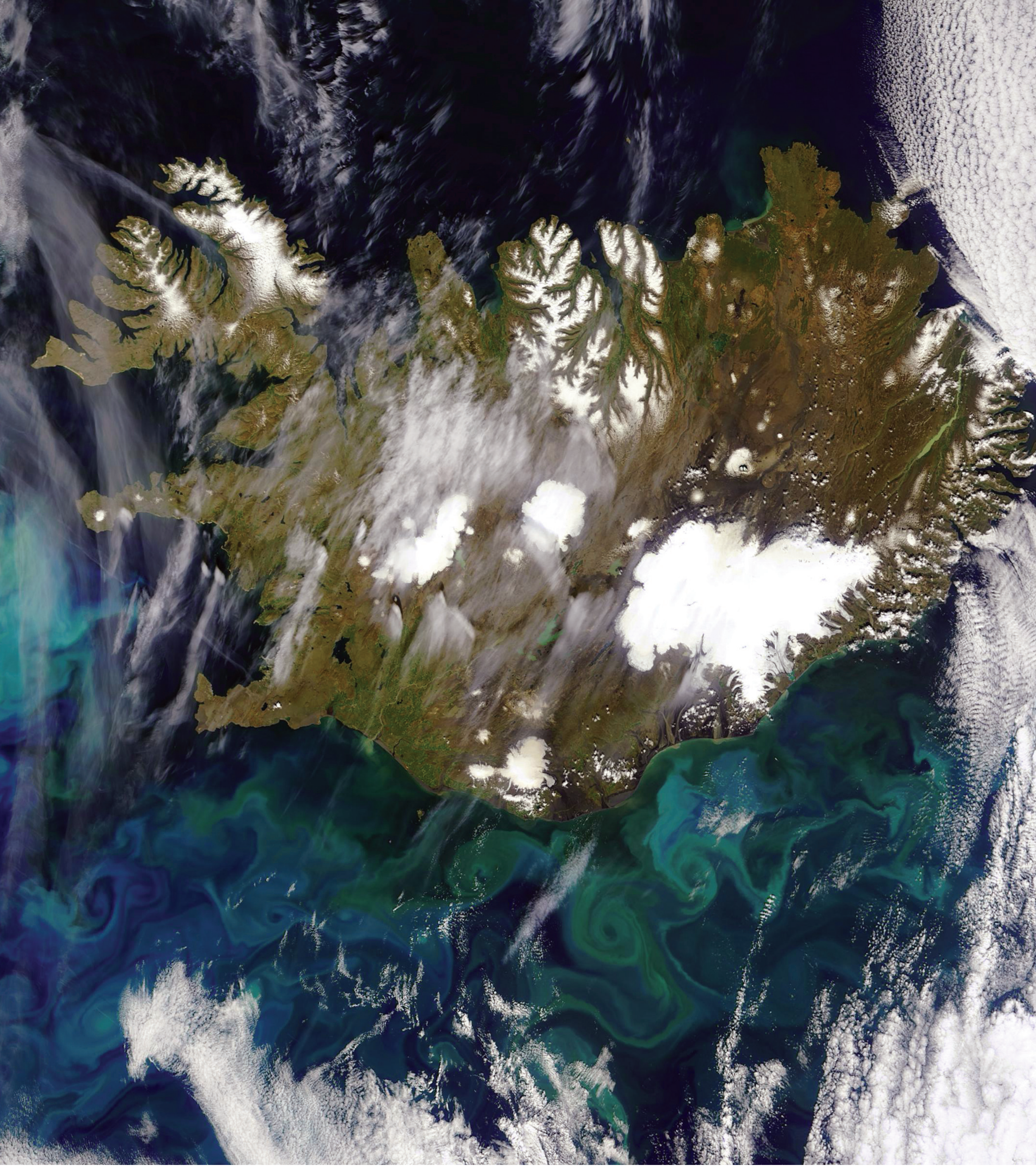
The story of this book sets out the scientific basis for our understanding of climate change. It is divided into four parts, beginning with a description of Earth's present climate system. We explain the workings and interactions of the atmosphere and the ocean; how they move heat around the planet and bring us familiar climate phenomena, such as the El Niño–Southern Oscillation and the monsoons; and the all-important carbon cycle, which determines the carbon dioxide content of the atmosphere. Part II explores the drivers of climate change. We define the scientific framework that enables us to systematically think about climate change—the related concepts of radiation balance and radiation forcing—and investigate the greenhouse effect and other drivers of climate change. Our knowledge of how the climate system works today rests, in part, on our knowledge of how it changed in the past. We therefore also delve into paleoclimate, focusing on the global climate record of the past 2.6 million years. Part III concerns the consequences of climate change. To appreciate how climate change *can* affect humanity, we first turn our attention to how humans *were* affected by climate change over roughly the past 10,000 years. We then describe climate change as it has been observed in the twentieth and twenty-first centuries and its consequences to date.

All this brings us to the future. Computer models of the climate system help us understand how climate may change in the coming decades and centuries. We therefore begin Part IV with a description of climate models and their projections of what might come to pass. No one knows what the future will bring, of course, so we devote some effort to casting climate as a matter of risk. To deal with an unknown future, humanity invented the concept of risk, in which cost-benefit analysis provides a basis for rational decision making in the face of uncertainty. We thus apply the concept of risk in the context of adaptation to climate change and attempts at mitigation. Among the many aspects of these efforts, it becomes immediately apparent that of paramount concern is our ability to control emissions from the burning of fossil fuels and to apply alternative technologies to satisfy the world's insatiable appetite for energy. This appetite is dominated by one overriding issue: how we are going to provide for the world's electricity needs. Because of its centrality to future climate, we have chosen to focus on this matter in the final chapter of this book, at the same time recognizing that the production of energy is now (and has been) a rapidly changing enterprise.

This book found the support of many people. One of the joys of its writing was how much we learned from each other and from our many colleagues, many of whom are at the Lamont-Doherty Earth Observatory of Columbia University. We are also indebted to Kent Short, Scott Mandia, Dennis Hartmann, Alessandra Grannini, Mingfang Ting, A. Park Williams, and several anonymous reviewers who suffered through early drafts of the manuscript and provided insightful suggestions for its improvement. The content of the book was also strongly influenced by the innovative legacy of climate courses taught at Columbia University, and we are grateful to the instructors who shared their support, insights, and materials over the years. Several colleagues deserve particular mention: Stephanie Pfirman, Jerry McManus, Yochanan Kushnir, Mark Cane, Ben Cook, Linda Sohl, Steve Cohen, and Louise Rosen. JES is also grateful to Henry and Lana Pollack, who inspired his transition into climate science and who remain aspirational examples of effective public communication and outreach. This book also would not have been possible without the unfailing enthusiasm and hard work of our editor, Patrick Fitzgerald, and the technical support of manuscript editor Irene Pavitt and designer Milenda Lee, all of Columbia University Press, and of Saebyul Choe of the American Museum of Natural History. Finally, none of this would have been possible without the inspiration, support, and patience of our families.

EDMOND A. MATHEZ
JASON E. SMERDON

Climate Change



Satellite view of Iceland and surrounding waters

Climate is a dynamic "system" that ultimately is driven by the energy of the Sun, but results from the dynamic interactions among Earth's atmosphere, ocean, rock, ice, and life—all of which are observable in this photograph. The lighter ocean colors are due to phytoplankton blooms. The image was taken by NASA's satellite *Terra* on June 21, 2004. (J. Descloitres, MODIS Rapid Response Team, NASA/Goddard Space Flight Center, Visible Earth, https://visibleearth.nasa.gov/view.php?id=71461)

PROLOGUE

"RAIN, HEAVY AT TIMES, will begin in late morning and continue into the evening hours as a cold front sweeps across the area . . ." Ah, the weather forecast—what would we do without it? There is no shortage of conversation about the weather, which, after all, touches our daily lives. For some, the weather is very important—especially if their harvest depends on it. For others, it is more tangential. We're thinking of ourselves here; on most days, we just want to know about our treks to work in New York City. Will rain or snow make it impossible or just more miserable than usual?

And then there is climate. What might a climate forecast be like?[1] "The next decade will bring persistent showers and mild temperatures from January through March and extensive periods of no rainfall at all throughout the summer months." Hmm . . . that seems a bit remote from our immediate worry of getting to work. Although it may appear harder to connect the implications of climate to our daily lives, it is relevant. Climate dictates the kinds of clothes we keep in our closets and the way the buildings around us are made. It may drive our decisions about where to live, when we decide to visit places around the world, and what kind of car we choose to buy. So how are they different, weather and climate?

Weather and Climate

Upon reflection, it becomes clear that there are essential differences between weather and climate, even though they are inextricably linked. *Weather* refers to conditions in the atmosphere at any one time. The familiar radar images on television show that local weather systems develop and dissipate rapidly over the course of hours to a day. On a continent-wide scale, weather systems form and decay over days to a week or so. A persistent weather system, such as a warm spell, may last for a couple of weeks or even more, especially in mid-latitudes, where the tracks of weather systems are commonly determined by the position of the polar jet stream, as chapter 1 explains.

Climate, in contrast, can be thought of as the "average weather" for a particular region over some period of time. We place "average weather" in quotes because climate itself is changing, so a weather average must always be defined over a specific time interval that may be different if determined over another. In any event, “region” can refer to the entire globe, as in global warming; to a large landmass, such as eastern North America; or to a small land area, as in the “microclimate” of a particular valley in a larger wine-producing region.

Although we have become adept at forecasting weather hours to a day or so ahead, predictions beyond that become progressively more uncertain with distance into the future. Weather is inherently chaotic. Strictly speaking, the term *chaotic* in this context means that small differences in initial conditions result in large differences in how a system will eventually develop. In other words, to predict weather accurately, we would have to know the temperature, humidity, barometric pressure, wind velocity, precipitation, and other characteristics of a weather system everywhere across an affected region, and even then prediction would be accurate for only the next week or two.

Being an average condition, climate is not chaotic—at least not in the same way that weather is. Instead, it displays stable and distinctive patterns of change on specific timescales. Examples include annual changes such as monsoons, which are shifts in winds that bring seasonal rains to a number of regions in the tropics and subtropics. They also include fluctuations that occur only every several years, the most notable of which is the El Niño–Southern Oscillation (ENSO) phenomenon, referring to the periodic shifts of winds and ocean currents that bring warm water to the equatorial eastern Pacific Ocean and dry conditions to the western equatorial Pacific, and that influence climate in far-flung parts of the globe.

What does all of this mean for those forecasts that we originally imagined? On a day-to-day basis, climatologists like to boil down the differences between climate and weather to their essence: *You dress for the weather and build a house for the climate.* Or how about: *Climate is what you expect; weather is what you get.* If you are a dog owner, you may prefer: *Weather is like the dog running back and forth, and climate is like the leash driving the ultimate path*. Whatever your preference—and you may have your own—these examples are illustrative of the differences and dependencies of weather and climate.

One additional point must be emphasized. Climate change is a long-term phenomenon. This inherently protracted characteristic, at least in terms of human timescales, creates one of the conundrums surrounding attempts to reduce carbon dioxide (CO_2) emissions from the use of fossil fuels, the main culprit in global warming. It is simply difficult to marshal either the individual or the collective will to make the changes necessary to avoid the negative impacts of global warming because they generally do not appear to affect our immediate lives.

The Climate System

Climate is a dynamic system resulting from the combined interactions of various parts of Earth with one another and with the Sun. The components include the *atmosphere*; the ocean (*hydrosphere*); glaciers, terrestrial ice sheets, and sea ice (collectively known as the *cryosphere*); the living biomass (*biosphere*); and even the solid Earth (*lithosphere*). Think of it as your body, with all its parts interacting in an interlocking whole. And like your body, the climate system is not just a set of physical interactions, but also a complex chemical system, with matter flowing through its various parts and influencing its characteristics.

The atmosphere, being the medium in which we live, is the part of the climate system that affects us most directly. The atmosphere contains greenhouse gases—the gases that absorb infrared (IR) radiation—and in this way, it keeps Earth's surface in a habitable temperature range. Indeed, without such gases, Earth's surface would be frozen and lifeless. The atmosphere also plays a major role in transporting heat and moisture around the planet. Because Earth is a sphere, the Sun's heat is more intense near the equator than near the poles. This uneven distribution generates winds that carry heat from the equator toward the poles and from the surface to the upper atmosphere. Additionally, the atmosphere is not isolated from the ocean. The ocean circulates, in part driven by the winds and guided by the positions of continents, and thereby also transports heat toward the poles. Indeed, the ocean holds far more heat than does the atmosphere, but it flows much more slowly. Many of these interactions are also important in the transport of moisture around the planet. For instance, much of the rain that falls on land was originally evaporated from ocean water. The atmosphere therefore takes up enormous amounts of moisture and redistributes it around the globe based on its large-scale patterns of circulation. Finally, the atmosphere also holds ozone (O_3), which shades the surface of Earth from much of the lethal ultraviolet (UV) radiation received from the Sun.

As for the chemical interactions, the most important are the exchanges of carbon among the atmosphere, ocean, and biosphere (which includes the dead biomass held mainly in soil). In fact, we can think of these spheres as reservoirs where nearly all the carbon on or near Earth's surface is stored. This description leads to the concept of the *carbon cycle*, referring to the flow of carbon among the various reservoirs. In months to decades, photosynthesis by plants and decay of organic materials affect the amount of CO_2 in the atmosphere, but over longer periods, it is the ocean that exerts the dominant control on atmospheric CO_2 content because the amount of carbon in the ocean is nearly 50 times that in the atmosphere. If we think of the climate system as something like our body, the atmosphere and the ocean are its main organs, and the carbon cycle is the circulation system that connects them to each other and to other organs.

Most of the carbon (more than 99.9 percent) on Earth exists not in the ocean, atmosphere, or biosphere (the "surface" reservoirs), but in a deep reservoir in the form of rocks—that is, the lithosphere. The lithosphere is part of the climate system mainly because carbon flows between it and the reservoirs on Earth's surface, but this flow is far slower than the flow of carbon among the surface reservoirs. Over millions of years, a close balance has apparently persisted between two processes:

- The flow of carbon from the surface to the rock reservoirs by means of the removal of CO_2 from the atmosphere and the ocean through the formation of carbonate and other carbon-bearing rocks
- The return of CO_2 to the atmosphere by means of the breakdown of those rocks at the high temperatures and pressures of the deep Earth

In fact, this long-term balance appears to have acted as a natural, planetary thermostat, maintaining conditions on Earth's surface that have allowed for liquid water to be stable and that have been conducive to the evolution and survival of life since nearly the beginning of Earth's history.

The different parts of the climate system also interact through *feedbacks*, or phenomena that amplify or diminish the forces that act to change climate. An example helps to envision them. As the Arctic warms due to the buildup of greenhouse gases, sea ice melts. As sea ice melts, there is less bright ice to reflect solar energy back to space, and the ocean absorbs more energy. The greater absorption of energy, in turn, further warms the ocean and overlying

TABLE P.1 DIFFERENT TIMESCALES OF SOME WEATHER AND CLIMATE PHENOMENA

Timescale	*Example phenomena*
Daily	Warm days and cool nights due to solar heating and Earth's rotation
3–7 days	Weather events, such as the passage of fronts
Months	Eastward-propagating weather disturbances across the tropical Indian and Pacific oceans due to planetary-scale fluctuations in wind patterns
Yearly	Warm summers, cool winters, and shifts in zones of precipitation due to the tilt of Earth's spin axis and its orbit around the Sun; monsoons, notably on the Indian subcontinent, due to summer heating of landmasses that draws moist winds off oceans
23–36 months	Periodic wind and temperature oscillations in the equatorial stratosphere due to internal atmosphere dynamics
2–7 years	ENSO events, in which changes in equatorial Pacific Ocean currents and winds result in dramatic shifts in rainfall in equatorial regions globally and in lesser shifts in the climate of some temperate regions
1–3 decades	Generally ill-defined oscillations, such as the Atlantic Multidecadal Oscillation, a fluctuation in ocean water temperature over the entire North Atlantic Ocean that affects temperature in adjacent landmasses
Centuries	Irregular fluctuations that have led to multi-century cold or warm periods, such as the Medieval Climate Anomaly (or Medieval Warm Period) and the Little Ice Age, the causes of which are uncertain but may be related to one or more natural phenomena, such as variations in solar irradiance and volcanism
10,000–100,000 years	Regular variations in orbital parameters (the slow oscillations in Earth's tilt relative to the orbital plane, precession, and eccentricity of its orbit around the Sun) that affect the amount of energy reaching the Northern Hemisphere and are responsible for the approximately 100,000-year glacial cycles of the past 1 million years
Millions of years	Changes in the positions of continents, in solar luminosity, and in the composition of the atmosphere, all of which affect climate globally

Source: J. R. Christy, D. J. Seidel, and S. C. Sherwood, "What Kinds of Atmospheric Temperature Variations Can the Current Observing Systems Detect and What Are Their Strengths and Limitations, Both Spatially and Temporally?," in *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*, ed. T. R. Karl et al. (Washington, D.C.: Climate Change Science Program, Subcommittee on Global Change Research, 2006), 29–46.

atmosphere, causing even more ice to melt. In this way, the melting of ice amplifies the warming due to greenhouse gases alone. This feedback in part accounts for why the Arctic is more sensitive to global warming than is the rest of the planet. Feedbacks can be complex and can operate in unpredictable ways, and they are one reason that projecting future climate is fraught with uncertainty.

The climate system is complicated in other ways, one of which is that the various climate phenomena operate on different timescales (table P.1). Some of these phenomena and their associated timescales are familiar—for example, the daily variations of warm days and cool nights, and the annual passage of the seasons. Other phenomena occur on longer or irregular intervals but on timescales that are understandable, and still others occur on timescales beyond the human experience and are consequently difficult to imagine. Our knowledge of the last may also be incomplete because the evidence for them is buried (commonly and literally) in the geological record.

Climate Change: Separating Facts from Fears

What we do know from the available records, both geological and observational, is that the climate is changing. Hardly a day goes by without some mention of it in the news. Earth's climate is warming; CO_2 and other greenhouse gases have been building up in the atmosphere mainly as a consequence of the burning of fossil fuel; and the scientific evidence is now overwhelming that this buildup is causing the warming. These statements are the *facts* of climate change.

Less certain are how much the climate will warm in response to growing emissions and to what extent the warming will change the world around us. Should the warming be substantial, it may have huge negative impacts on biodiversity, ecosystems, agriculture, ocean life, the global economy, and the well-being of human societies everywhere. These possible results are the *fears* of climate change.

It is important to separate the facts from the fears. The facts give us insight, but the fears reflect the *risks*. Ultimately, we have to understand the risks if we are to develop intelligent policies to deal with global warming. To assess the risks, we need the knowledge, so let us start with the facts.

OBSERVATIONS OF CLIMATE CHANGE: THE FACTS

In addition to CO_2, the greenhouse gases include methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and water vapor (H_2O). These gases reside mostly in the *troposphere*, the lower 10 to 15 kilometers (30,000–50,000 feet) of the atmosphere, where the weather occurs. Here, the greenhouse gases absorb heat radiated from Earth's surface and thus act as a giant insulating blanket.

Greenhouse gases have been building up since the beginning of the industrial age, but only since 1958 has the CO_2 content of the atmosphere been measured directly, beginning first on the top of Mauna Loa in Hawai'i, as described in chapter 4.[2] The remarkable Mauna Loa record shows that the amount of atmospheric CO_2 has been continuously climbing over the years. In 1958, the average CO_2 content of the atmosphere was 315 parts per million (ppm) by volume (0.0315 percent); by 2015, it had reached about 400 ppm and was rising at a rate of nearly 3 ppm a year. Both the rate of increase and the amount of CO_2 presently in the atmosphere are greater than at any time in the past 800,000 years, the time over which the most detailed paleoclimatic record of atmospheric CO_2 content exists, and probably much longer.[3] Furthermore, a number of observations make quite clear that the CO_2 is originating mainly from the burning of fossil fuels.

At the same time, global mean surface air temperature has been rising, too. The warming began around 1910 and has proceeded in two distinct intervals, the first from 1910 to 1940, and the second beginning in the late 1970s and continuing. From 1880 to 2012, global mean surface air temperature increased by 0.85°C (1.53°F), and over the past three decades, the rate of increase has accelerated to 0.27°C (0.49°F) per decade.[4]

What is causing the warming? The evidence is overwhelming that it is a result of the rising levels of greenhouse gases in the atmosphere. First, there is the basic physics: greenhouse gases absorb radiant heat, or infrared energy, which we know from measurement and observation, and such energy is being emitted from Earth's surface. As was recognized more than a century ago, the climate therefore *should* warm as the concentration of greenhouse gases in the atmosphere increases.

Second, there are no other known natural forces external to the climate system that can account for the warming. For instance, some have suggested that changes in the amount of solar irradiance (that is, the amount of sunlight) reaching Earth may be causing the warming rather than the increase in the greenhouse gas content of the atmosphere. There is certainly indirect evidence that irradiance does change with time and that this may explain some of the cool and warm spells in the past. But except for the 11-year sunspot cycle, which represents only a minuscule fluctuation in irradiance, there have been no detectable changes in solar output since the advent of precise measurements by satellite in 1978, yet climate has rapidly warmed since then.[5]

Internal variations in the climate system—that is, fluctuations occurring on timescales of years to multiple decades and resulting mainly from the system's dynamic nature—may conceivably account for warming, at least regionally. These variations include phenomena such as ENSO and the Atlantic Multidecadal Oscillation (AMO), both of which are oscillatory phenomena in the ocean and atmosphere that result in large-scale redistributions of heat and are discussed fully in chapter 3. However, a variety of *observations* argue against internal variations as being responsible for the warming.

First, warming has been occurring more or less everywhere—it is a global, not a regional, phenomenon, as would be expected if the warming were due to internal variability.[6] Second, the lower atmosphere below about 10 kilometers (33,000 feet) has also been warming, while parts of the upper atmosphere have been cooling, as expected from the basic theory of greenhouse gas warming. Third, both the annual average maximum (daytime) temperature and the annual average minimum (nighttime) temperature have increased, but the nighttime temperature has increased more than the daytime temperature. This observation is consistent with what would be expected from increased insulation by greenhouse gases, as explained in chapter 5. Fourth, the oceans have been warming by far more than can be accounted for by natural internal variations in the climate system.[7]

Thus CO_2 and other greenhouse gases are increasing in the atmosphere, and at the same time, Earth's climate is warming. The scientific evidence overwhelmingly points to the buildup of greenhouse gases in the atmosphere as the cause of the warming because (1) it is an expectation of the basic physics, (2) it is consistent with *all* the observations of the present-day climate system and the recent record of climate change, and (3) no one has found an alternative hypothesis that can account for those observations.

POTENTIAL CONSEQUENCES OF CLIMATE CHANGE: THE FEARS

The fears concern how much the planet will warm and what the repercussions may be, but there is much uncertainty about this future. Climate change permeates the entire environment, so numerous effects, ranging from loss of sensitive ecosystems to increased occurrences of extreme weather events, appear likely. But the more profound and more distant potential consequences are those that are more uncertain.

Two potential ramifications that may have a severe impact on society illustrate both the fears and their associated uncertainties. The first and, perhaps, the more frightening is the possibility of harsh and extensive droughts significantly affecting worldwide agriculture and resulting in widespread famine. A number of regions are particularly vulnerable to drought, including western North America, the eastern Mediterranean, Southeast Asia, and the Sahel of Africa (the southern borderland of the Sahara Desert). About 1,000 years ago, for example, western North America experienced a number of "megadroughts," each of which lasted for several decades over a 300-year interval of relative warmth.[8] Such megadroughts have not been seen since. The megadroughts, and the multiyear droughts that have plagued these areas since, appear to be related to conditions in the tropical oceans, but exactly how those conditions influence rainfall patterns is not completely understood. The theory is that warming increases the probability of the occurrence of megadroughts; the fear is that such droughts will occur and have severe economic consequences.[9]

History is replete with examples of changes in climate that caused localized famine, which, in turn, resulted in massive societal disruptions, including conflict. In today's world, where trade is global and many economies are intertwined, we might expect localized disruptions to play out differently than in the past. But maybe not. While warming increases the likelihood of drought, it also increases the likelihood that severe and extensive droughts could occur simultaneously in many of the world's major food-growing regions. Although this may not be likely, especially anytime soon, it is not too difficult to imagine global famine and a cascade of dire and largely unforeseen consequences that follow. History teaches us that this is not an idle concern for the modern world, as demonstrated in chapter 12.

Substantial sea-level rise is the second serious concern. Sea level is currently rising at a rate of 3.2 ± 0.4 millimeters (0.13 inch) a year, equivalent to 32 centimeters (13 inches) a century.[10] The main contributions are the melting of glaciers, thermal expansion of the ocean (warm water is less dense than cold water and therefore occupies more space), and loss of ice from the Greenland and West Antarctic ice sheets. How much or how quickly Greenland and Antarctic ice will disappear is poorly constrained, so the extent of future sea-level rise is uncertain. This is reflected in the numerous estimates of twenty-first century sea-level rise that range from about 30 to 150 centimeters (1–5 feet).[11]

The stakes, nonetheless, are high. Worldwide, two-thirds of the cities with populations of more than 5 million people are vulnerable to the effects of rising sea level (the most serious of which are flooding during storms and coastal erosion). A sea-level rise of just 0.5 meter (20 inches) could threaten 10 percent of the world's population, amounting to some 700 million people, 75 percent of whom live in Asia. The rise will be gradual, but even a 1-meter (40-inch) rise in this century will impose enormous economic costs and possibly also disrupt society in ways that are difficult to foresee.

Thinking About the Future in the Face of Uncertainty

As noted, we know neither exactly how much or how rapidly sea level will rise, nor how drought will affect the global food supply in the distant future. Yes, we are, for the most part, ignorant. But this is exactly the point. We are smart enough to know that we are putting ourselves at risk, but we are not so smart that we can precisely gauge the risk.

Speaking of risk, this concept was invented to deal with an uncertain future. Most of us buy insurance to mitigate risk, such as the personal financial risk associated with a house burning down. We can also buy insurance, in a sense, to alleviate the effects of climate change by adopting policies that seek to minimize the change. But there is a big difference in the two cases: while insurance should allow us to buy a new house, if climate change unleashes globally drastic calamities, unlikely as this might be, we are out of luck because we will not be able to buy a new planet. The important points are that efforts to limit climate change and to mitigate its impacts are exercises in risk management, and that understanding the problem in that light should help guide our response. Again, this perspective is developed in chapter 12.

It is worth pointing out two characteristics of the climate system that further exacerbate the uncertainty of our future. First, the climate system possesses *inertia*: it takes time for the system to reach a new balance in response to the forces that have acted to change it. In other words, even if greenhouse gas emissions were to be immediately capped at today's levels, warming would continue for several decades. By one estimate, there is currently more than 0.6°C (1.1°F) worth of warming already locked in, or "in the pipeline," since the year 2000.[12] Second, as the climate changes, it can reach *tipping points*, or large abrupt shifts in response to the forces that were gradually causing it to change. The geological record is replete with instances of abrupt and dramatic shifts in climate.

On a related note, students often ask us why, considering that climate has changed dramatically in the past in response to only natural forces, we should concern ourselves with human-induced changes. The answers are simple. First, complex societies were not around to experience the huge shifts of the past. The climate of the past 11,600 years, known to geologists as the Holocene, has been stable by the standards of the past 1 million years, and complex societies have been around for only about the past 6,000 of those years. Second, the current human-induced changes are proving to be far more rapid than any natural changes. So the climate system has within it the possibility of bringing about changes that are both more dramatic and more rapid than societies have ever experienced, and that could challenge their abilities to adapt.

The Story

This book is divided into four parts and takes a somewhat unconventional approach to presenting its subject. Part I is not about climate change; rather, it is about the climate system. The concept of the Earth system, of which the climate system is a part, is fundamental in geological thought, and understanding how the climate system works—in other words, how the components of the climate system interact dynamically and chemically with one another—is a necessary prerequisite to understanding how climate responds to the forces that are acting to change it. Thus Part I recounts the fundamental characteristics of the atmosphere and the ocean, and the ways in which they interact dynamically and chemically with each other through the carbon cycle.

Part II introduces the equally fundamental concept of radiation balance, which is the scientific framework that has emerged for thinking about climate change. Here we describe the many factors that influence radiation balance. We also explore the fascinating story of past climate changes, or *paleoclimate*, which gives us essential insight into how climate is changing today and how it will change in the future as more greenhouse gases are injected into the atmosphere. The story focuses on the past 3 million years, but we also visit a more distant time to seek additional insight.

Part III concerns the numerous consequences of climate change. It begins by exploring how climate change since the end of the last glaciation has influenced the course of human history. It then documents the rapid increase in global temperature that has occurred over the past century and some of the changes that we are beginning to experience as a consequence of that warming. These include changes in patterns of precipitation and drought and in the occurrence of severe weather events. The Arctic is especially sensitive to warming and, at the same time, has an important influence on global climate, so we also investigate the changes there. As noted, sea-level rise is an important concern, leading us to examine what is happening to the Greenland and West Antarctic ice sheets.

Part IV is about the future. Although climate models tell us a great deal about the behavior of today's climate, they are the main means of portraying future climate, and for that reason they are included here. We argued earlier that mitigating climate change is an exercise in risk management, and recognizing this serves as a basis for developing intelligent policies to alleviate the effects. For these reasons, we devote some attention to climate risk. Finally, obviously central to the future is how the world is going to satisfy its insatiable appetite for energy while keeping carbon emissions in check. It is the vastness of the energy-producing enterprise that astonishes, and we take on this subject as the final chapter.

That is the story. It is complex, it suggests that we face a difficult future, but it also implies that we can avoid the most dire consequences of climate change by intelligent action.