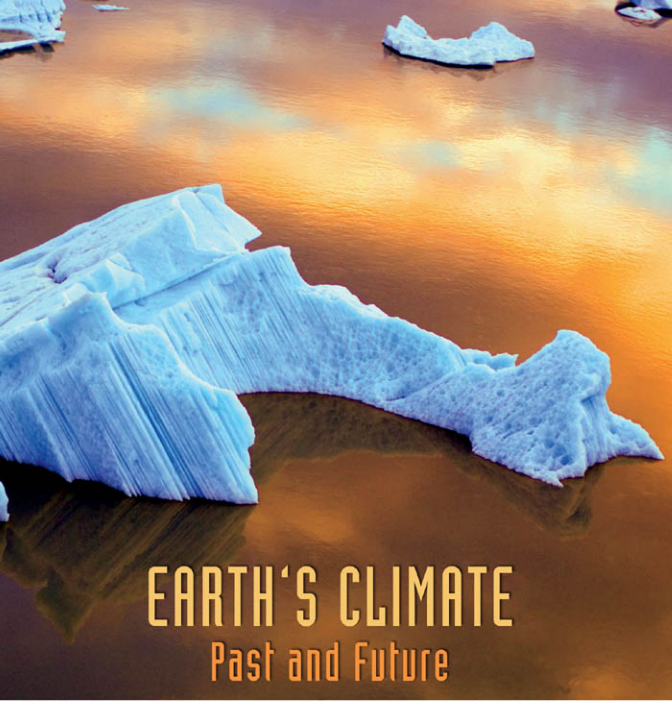

EARTH'S CLIMATE
Past and Future

Third Edition

WILLIAM F. RUDDIMAN

Earth's Climate

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Earth's Climate

PAST AND FUTURE

Third Edition

WILLIAM F. RUDDIMAN

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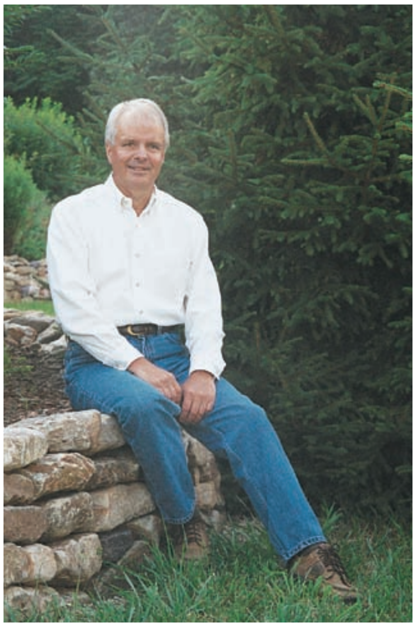
*To my many colleagues who have investigated
the science of climate change because they find it an endlessly
fascinating subject, and who in recent years have in some
cases done so under duress from those who refuse to
accept what the science is telling us*

About the Author



WILLIAM F. RUDDIMAN holds a 1964 undergraduate degree in geology from Williams College and a 1969 Ph.D. in marine geology from Columbia University. He worked at the U.S. Naval Oceanographic Office from 1969 until 1976 as a senior scientist/oceanographer and then returned to Lamont-Doherty Observatory as a senior research associate. He was associate director of the Oceans and Climate Division from 1982 to 1986 and an adjunct professor in the Department of Geology from 1982 to 1991. He moved to the University of Virginia in 1991 as a professor in the Department of Environmental Sciences and served as department chair from 1993 to 1996. At Virginia, he taught courses in climate change, physical geology, and marine geology. He has participated in fifteen oceanographic cruises and was co-chief on leg 94 of the Deep-Sea Drilling Project and leg 108 of the Ocean Drilling Project.

Professor Ruddiman's research interests have ranged across aspects of climate change on several time scales. His early research with Andrew McIntyre focused on orbital-scale climate change in and around the north and equatorial Atlantic Ocean. He was a member of the CLIMAP project from 1978 to 1984 and Project Director in 1980–1981. He was a member of the COHMAP project from 1980 until 1989 and served on the steering committee throughout that time. Along with other COHMAP scientists, he co-edited the 1993 volume *Global Climate Since the Last Glacial Maximum.*

In the late 1980s and the 1990s, his research focused mainly on the longer-term (tectonic-scale) physical and geochemical effects of uplift of the Tibetan Plateau and other high topography on regional and global climate. In 1997, he edited *Tectonic Uplift and Climate Change,* published by Plenum Press. His work on plateau uplift with colleagues Maureen Raymo, John Kutzbach, and Warren Prell has been featured in BBC and NOVA television documentaries.

Since 2001, his research has focused on the effects of early agriculture on greenhouse-gas concentrations. His early anthropogenic hypothesis proposes that releases of carbon dioxide and methane caused by farming drove an anomalous rise in greenhouse-gas concentrations during the last several thousand years. In 1995, his Princeton University Press book *Plows, Plagues, and Petroleum* won the Phi Beta Kappa award for best science book of the year.

Professor Ruddiman is a fellow of the Geological Society of America and the American Geophysical Union. In 2010, he received the Charles Lyell Medal from the Geological Society of London. In 2012, he received the Distinguished Career Award from the American Quaternary Association.

He lives on a hillside in the Shenandoah Valley with his wife, Ginger, and an ever-changing bunch of dogs. His hobbies include rock-wall building, gardening, and walking the Appalachian Mountains, remnants of the continental collisions that produced the supercontinent Pangaea and the rocks now featured in his walls.

Brief Contents

Contents

Preface

Several years after the second edition of *Earth's Climate* was published in 2007, the field of climate science has advanced far enough to warrant a new edition. During that time, an even stronger consensus has developed that rising greenhouse-gas concentrations in the atmosphere caused by human activities are the primary factor behind the warming of our planet. In several cases, changes during just these last few years have occurred faster than previously expected. Sea ice has retreated and thinned far more rapidly since 2006, the Greenland ice sheet has melted at an accelerating rate, and global sea level is rising faster than it did during the 1900s. This edition addresses this new evidence for anthropogenically driven global warming. It also addresses important new advances in understanding past climates.

New to This Edition

STRUCTURING AND UPDATING With one exception, the structure remains the same as in the second edition. Part 1 again covers introductory material, but Chapter 2 from the first edition ("Earth's Climate System Today") has been restored to this edition. This chapter provides a valuable summary of the basic operation of the climate system for use by instructors and students.

The formal treatments of oxygen and carbon isotopes are again placed in Appendices 1 and 2 so as not to break the flow of the text with these more technical treatments. Within the text, more functional definitions are provided (for example, more positive oxygen isotope ratios represent some combination of larger ice sheets and colder ocean temperatures).

Several chapters address significant advances in scientific understanding of complex problems that have occurred in recent years. Prominent advances include the cause of cyclic orbital-scale changes in ice sheet size (Chapter 11) and of millennial-scale changes in climate (Chapter 14). Responses of components of the climate system to global warming have also been updated to recent years (Chapter 17).

STREAMLINED TEXT All of the chapters move from introductory material to final conclusions along a clear logical path. At or near the end of each chapter or major section, "In Summary" statements in the text are marked by tan shading to make them easier to find.

Building on the Second Edition

The third edition retains several successful approaches from the first two editions.

MULTIDISCIPLINARY SCOPE The story of Earth's climate draws on many disciplines—geology, ecology, paleobotany, glaciology, oceanography, meteorology, biogeochemistry, climate modeling, atmospheric chemistry, and hydrology, among others. This range of disciplines is a large challenge, both to students for whom all of the science in this field is new, and also to instructors who may specialize in one or two of the many research fields and time scales of climate change. This text eases this challenge through logical, step-by-step explanations of critical material, accompanied by attractive color graphics that summarize key points and by lists of follow-up resources for background material.

FOLLOWING EARTH'S TIMELINE Like the previous editions, this edition explores the climatic responses of Earth's major systems (ice, water, air, vegetation, and land) as they developed through Earth's history. The structure again follows time's arrow, moving from the earliest known climates all the way to historical, modern, and future changes. The main reason for this structure is that this is the way Earth's climate actually developed, and so it is the most natural way to tell the story. In addition, shorter-term climate changes tend to ride on the back of longer-term changes, and the longer-term changes need to be understood first in order to provide context to those that are of more recent origin.

MYSTERY-SOLVING APPROACH Another advantage of organizing the book by time scale is that students see a coherent, integrated view of the evidence of climate change and the competing hypotheses posed to explain the evidence within each time scale. Because the central dynamics of science are the interactions among data, theory, and theory testing, this integrated approach makes science come alive. The evidence of past climatic changes summarized at the start of each chapter leads to the obvious question: What caused the observed changes? The chapters then describe and evaluate the hypotheses proposed to explain the observations. Students are invited to be detectives in the problem-solving process by weighing the proposed hypotheses against a range of data and other methods, including experiments with climate models. From my own teaching experience, the best students are generally intrigued to find out that so much work still remains to be done in this young field of science.

The major themes of the book remain the same as in the first edition:

- The causes (forcing) of climate change
- The natural response times of the many components of Earth's climate system
- Interactions and feedbacks among these numerous components
- The role of carbon as it moves within the climate system at each time scale

STRUCTURE The structure of this edition of *Earth's Climate* is similar to its predecessor. Part I surveys the field of climate science and the approaches used to unravel Earth's climatic history. Parts II through V describe how Earth's climate has changed at progressively shorter time scales: tectonic-scale and earlier changes in Part II; orbital-scale changes in Part III; deglacial and millennial changes in Part IV; and historical, recent, and future changes in Part V. Progressively more recent intervals receive increasingly detailed treatment because the climate changes can be resolved in finer detail. This approach also helps overcome the complexity of the climate system by focusing on the range of issues critical to each time scale.

ALTERNATIVE VERSIONS W. H. Freeman partners with CourseSmart to provide a low-cost subscription to the text in e-Book format. CourseSmart e-Books can be read online or offline, as well as via free apps for iPad, iPhone, iPod Touch, Android devices, and Kindle Fire. Students are able to take notes, highlight important text, and search for key words. For more information, or to purchase access to the text, visit www.coursesmart.com.

There is also a loose-leaf version of the text available at a discounted price. To order *Earth's Climate*, Third Edition, in loose-leaf, please use ISBN 1-4641-5282-9.

A Growing Audience for Earth's Climate

Adoptions of *Earth's Climate* have grown during the 13 years since the first edition was published. Initially, the book was a popular choice for upper undergraduate courses in earth science departments, often replacing or supplementing classical subjects like historical geology or sedimentology and stratigraphy. Adoptions also occurred in many related disciplines, such as environmental sciences, geography, ecology, botany, and oceanic and atmospheric sciences.

More recently, many instructors have realized that *Earth's Climate* can also be used in introductory-level courses for students who do not plan to major in science but want to satisfy a science requirement. Because climate change is in the news every week, student interest in such courses is running at a high level and these courses are growing. Introductory climate courses at several universities that have used the first two editions of *Earth's Climate* have attracted hundreds of students per term.

Using a book like this at the introductory level requires lecturing and testing at an appropriately generalized (conceptual) level and de-emphasizing some of the quantitative material. I think of students in introductory courses as members of a (it is hoped) attentive jury. They do not need to have prior knowledge of the subject, but they can reasonably be expected to follow the lines of argument carefully, understand the issues at hand, and draw basic conclusions from what they learn.

Instructors who are considering teaching such an introductory course should find the third edition helpful. As before, instructors can bypass the more advanced material set off in boxes titled Looking Deeper into Climate Science. The three other kinds of boxes (Climate Interactions and Feedbacks, Climate Debate, and Tools of Climate Science) are part of the basic text and should not be a major problem for students in introductory courses.

Given my experience teaching this course at the introductory level, I have written a short guide for instructors that can be found at www.whfreeman.com/earthsclimate3e.

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Framework of Climate Science

part I

Large changes in climate naturally pique our curiosity. In the recent past, the hot, dry interval that produced the Dust Bowl of the 1930s forced thousands of farmers from the Great Plains westward to California. A century earlier, air temperatures were cooler than now, and valley glaciers in Europe occupied positions well down the sides of mountains compared with their higher modern elevations. Considerably further back in time, 21,000 years ago, climate was so cold that enormous ice sheets covered Canada and northern Europe, and sea level was some 120 meters (~400 feet) lower than it is today because of the vast amount of ocean water stored on land as ice. Much further back, 100 million years ago, warmer conditions kept ice from forming on the face of Earth, even at the South Pole.

Changes in the distant past occurred for natural reasons, some of them well understood and others still in the process of being unraveled. Climate science is a young science, and many exciting discoveries lie ahead.

Today, Earth's climate is rapidly warming, and it is clear that humans are a major cause of this change. As scientists work to find out how large the warming will be, part of the answer will come from understanding changes that occurred in the past. The chapters in Part I provide a general framework for understanding climate change by addressing several questions:

- What are the major components of Earth's climate system?
- How does climate change differ from day-to-day weather?
- What factors drive changes in Earth's climate?
- How do the many parts of Earth's climate system react to these driving forces and interact with each other?
- How do scientists study past climates as a way to project the changes that lie in our future?

Mountain glacier advances during the Little Ice Age. A view of the village of Argentiere in the valley of Chamonix during mid-1800's shows the Argentiere glacier extending far down the mountainside. (MARY EVANS PICTURE LIBRARY/THE IMAGE WORKS.)

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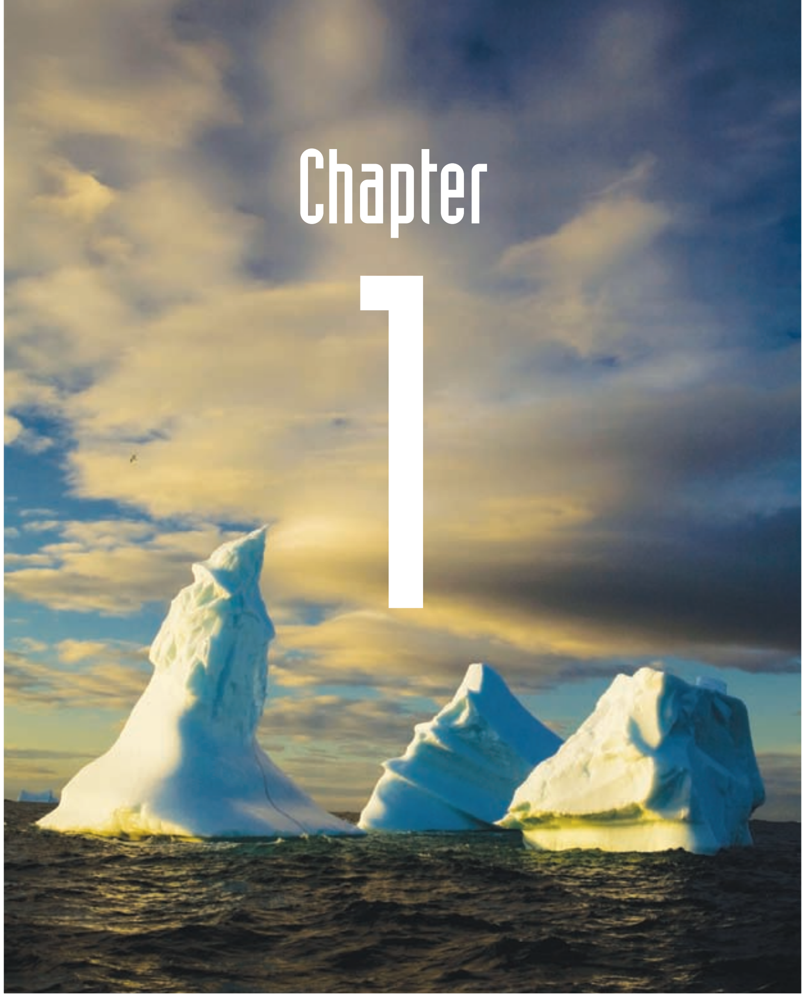


Overview of Climate Science

Life exists nearly everywhere on Earth because the climate is favorable. We live in, on, and surrounded by the climate system: the air, land surfaces, oceans, ice, and vegetation. Climate change is an important thread in the tapestry of Earth's history, along with the evolution of life and the physical transformations of this planet.

But the study of climate also matters for a practical reason: it is relevant to the climatic changes we face in the near future. We have left an era when natural changes governed Earth's climate and have now entered a time when changes caused by human activity predominate. This emerging era is widely referred to as "the Anthropocene."

This chapter surveys the natural factors that cause Earth's climate to change. It also reviews how the field of climate science came into being, how scientists study climate, and how an understanding of the history of climate change can inform us about changes looming in our near future.

1 Climate and Climate Change

Even from distant space, it is obvious that Earth is the only habitable planet in our solar system (Figure 1-1). More than 70% of its surface is a welcoming blue, the area covered by life-sustaining oceans. The remaining 30%, the land, is partly blanketed in green, darker in forested regions and lighter in regions where grass or shrubs predominate. Even the pale brown deserts and much of the white ice contain life.

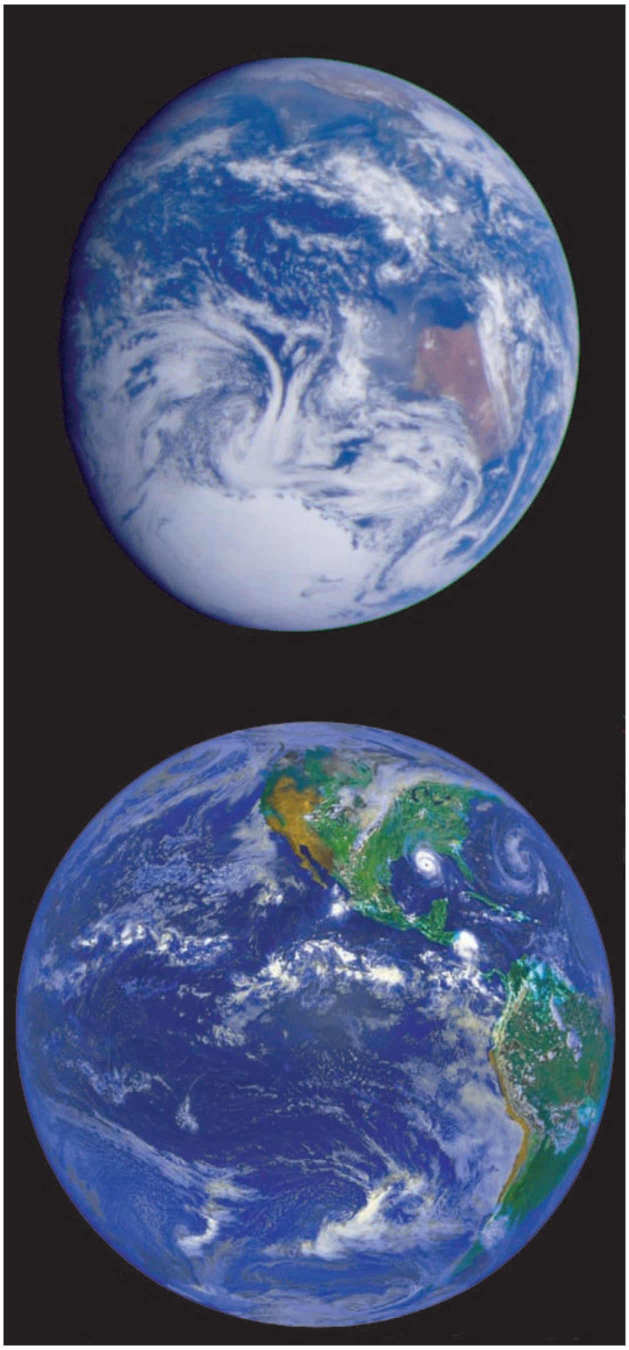


FIGURE 1-1
The habitable planet

Even seen from distant space, most of Earth's surface looks inviting to life, especially its blue oceans and green forests, but also its brown deserts and white ice. All these areas are prominent parts of Earth's climate system. (NASA.)

Earth's favorable climate enabled our planet to evolve and sustain life. **Climate** is a broad composite of the average condition of a region, measured by its temperature, amount of rainfall or snowfall, snow and ice cover, wind direction and strength, and other factors. Climate change specifically applies to longer-term variations (years and longer), in contrast to the shorter fluctuations in **weather** that last hours, days, weeks, or a few months.

Earth's climate is highly favorable to life both in an overall, planetwide sense and at more regional scales. Earth's surface temperature averages a comfortable 15.5°C (60°F) and much of its surface ranges between 0° and 30°C (32° and 86°F) and can support life (Box 1-1).

Although we take Earth's habitability for granted, climate can change over time, and with it the degree to which life is possible, especially in vulnerable regions. During the several hundred years in which humans have been making scientific observations of climate, actual changes have been relatively small. Even so, climatic changes significant to human life have occurred. One striking example is the advance of valley glaciers that overran mountain farms and even some small villages in the European Alps and the mountains of Norway a few centuries ago because climate was slightly cooler than now. Those glaciers have since retreated to higher positions, as shown in the introduction to this part of the book.

Scientific studies reveal that historical changes in climate such as the advance and retreat of this glacier are tiny in comparison with the much larger changes that happened earlier in Earth's history. For example, at times in the distant past, ice covered much of the region that is now the Sahara Desert, and trees flourished in what are now Antarctica and Greenland.

1-1 Geologic Time

Understanding climatic changes that occurred in the past requires coming to terms with the enormous span of time over which Earth's climatic history has developed. Human life spans are generally measured in decades. The phases of our lives, such as childhood and adolescence, come and go in a few years, and our daily lives tend to focus mainly on needs and goals that we hope to satisfy within days or weeks.

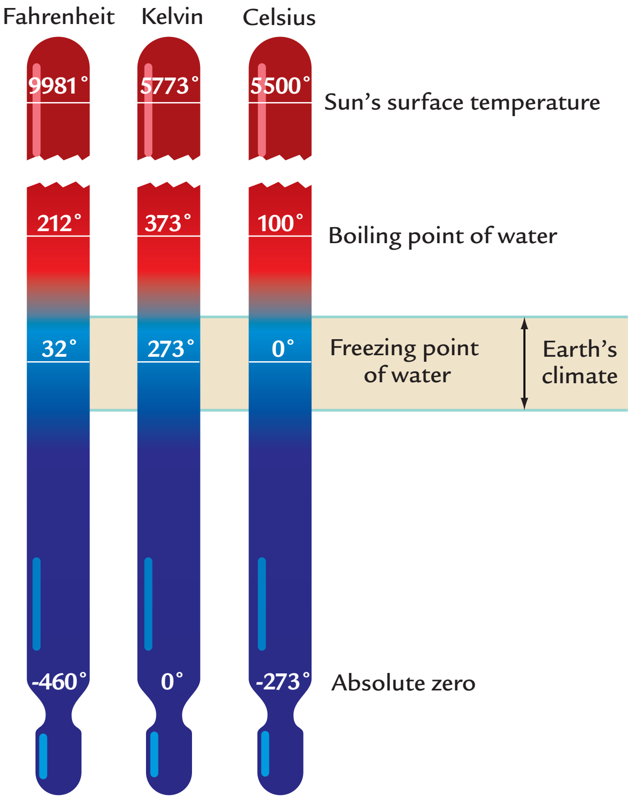
Almost all of Earth's long history lies immensely far beyond this human perspective. Earth formed 4.55 billion years (Byr) ago (4,550,000,000 years!). Most of the earliest part of Earth's history is known only in a sketchy way. One reason for this gap in our knowledge is the climate system itself: the relentless action of air

Tools of Climate Science

Box 1-1

Temperature Scales

Three temperature scales are in common use in the world today. For day-to-day nonscientific purposes, most people in the United States use the Fahrenheit scale, developed by the German physicist Gabriel Fahrenheit. It measures temperature in degrees **Fahrenheit** (°F), with the freezing point of water at sea level set at 32°F and the boiling point at 212°F.



Temperature scales Scientists use the Celsius and the Kelvin temperature scales to measure climate changes. Temperatures at Earth's surface vary mainly within a small range of −50°C to +30°C, just below and above the freezing point of water. (ADAPTED FROM W. F. KAUFMAN III AND N. F. COMINS, *DISCOVERING THE UNIVERSE*, 4TH ED., © 1996 BY W. H. FREEMAN AND COMPANY.)

Most other countries in the world, and most scientists as well, routinely use the Celsius (or centigrade) scale developed by the Swedish astronomer Anders Celsius. It measures temperature in degrees **Celsius** (°C), with the scale set so that the freezing point of water is 0°C and the boiling point of water is 100°C.

These equations convert temperature values between the two scales:

$$T_C = 0.55\,(T_F - 32) \qquad T_F = 1.8T_C + 32$$

where T_F is the temperature in degrees Fahrenheit and T_C is the temperature in degrees Celsius.

Scientific calculations generally make use of a third temperature scale developed by the British physicist Lord Kelvin (William Thomson) and known as the **Kelvin** scale. This scale is divided into units of Kelvins (not degrees Kelvin). The lowest point on the Kelvin scale (absolute zero, or 0K) is the coldest temperature possible, the temperature at which motions of atomic particles effectively cease. The Kelvin scale does not have negative temperatures because no temperatures colder than 0K exist.

Temperatures above absolute zero on the Kelvin scale increase at the same rate as those on the Celsius scale, but with a constant offset. Absolute zero (0K) is equivalent to −273°C, and each 1K increase on the Kelvin scale above absolute zero is equivalent to a 1°C increase on the Celsius scale. As a result, 0°C is equivalent to 273K.

and water on Earth's surface has eroded away many of the early deposits that could have helped us reconstruct and understand more of this history.

This book focuses mainly on the last several hundred million years of Earth's history, equivalent to less than 10% of its total age. Our focus is limited in this way because many aspects of Earth's history are only vaguely known far back in the past. But more information becomes available from the younger part of the climatic record, and our chances of measuring and understanding climate change improve.

Even the last 10% of Earth's history covers time spans beyond imagining. The climate scientists who study records spanning hundreds of thousands to hundreds of millions of years understand time only in a technical way—basically as a means of cataloging and filing information. Geologists often refer to these unimaginably old and long intervals as "deep time," hinting at their remoteness from any real understanding. Like the scientists who study climate change, you will learn in this book to catalog deep time in your own mental file, even if you cannot comprehend its vastness in a tangible way.

The plot of time on the left in Figure 1-2 shows that much of the focus of this book (Parts III through V) fits into a fraction of Earth's history too small even to show up on a simple linear scale. One way to overcome this problem is to start again with a plot

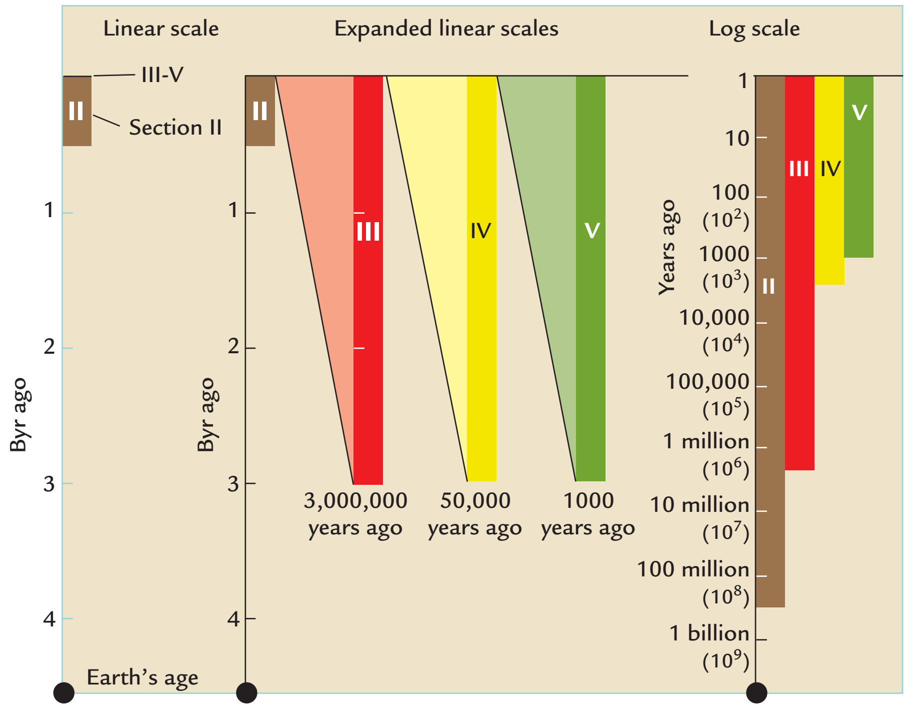


FIGURE 1-2
Earth history
Earth's age is 4.55 billion years. Most of the focus of this book fits into a very small fraction of this immense interval and can be represented only by a series of magnifications or by plotting time on a log scale that increases by factors of 10.

of Earth's full age, but progressively expand out and magnify (blow up) successively shorter intervals to show how they fit into the whole (Figure 1-2 center). Another method is to plot time on a logarithmic scale that increases by successive jumps of a factor of 10 (Figure 1-2 right). This kind of plot compresses the longer parts of the time scale and expands the shorter ones so that they all fit onto one plot.

1-2 How This Book Is Organized

Within its focus on the most recent 10% of Earth's age, this book is organized by time scale. Part II mainly covers climatic changes during the last several hundred million years, an interval during which dinosaurs appeared and later abruptly disappeared, while mammals evolved from primitive to diverse forms. Part III looks at the last 3 million years, the time span when our primitive ancestors evolved into us. Part IV explores changes over the last 50,000 years, an interval that spans large oscillations during the last major glaciation, the maximum development of that glaciation and the subsequent deglaciation that led to our present interglacial climate. Part V starts with the story of how our fully human ancestors initially lived a primitive hunting-and-gathering life and then developed agriculture, prior to the first human civilizations. Part V then focuses in from the last 1,000 years to the current industrial era and projects forward into the future.

This progression from longer to shorter time scales is a natural way to look at the climate system because faster changes at shorter time scales are embedded in and superimposed upon slower changes at longer time scales. At the longest time scale, a slow warming between 300 and 100 million years (Myr) ago was followed by a gradual cooling during the last 100 Myr (Figure 1-3A). This gradual cooling led to the appearance of Antarctic ice and later to the massive northern hemisphere ice sheets that advanced and retreated many times during the last 3 million years at cycles of several tens of thousands of years (Figure 1-3B). Superimposed on these climatic cycles were shorter oscillations that lasted a few thousand years and were largest during times when climate was colder (Figure 1-3C). The last 1,000 years has been a time of relatively warm and stable climate, with much smaller oscillations (Figure 1-3D).

The way the climatic changes at these various time scales are linked is analogous to the way that cycles of daily heating and nighttime cooling are superimposed on the longer seasonal cycle of summer warmth and winter cold. To understand the extreme heat reached during a specific afternoon in July in the Northern Hemisphere, it first makes sense to consider that such an afternoon occurs in the larger context of the hottest season of the year, and then to factor in the additional contribution from daytime heating. For a similar reason, it makes sense to follow time's arrow and trace climate changes from older to younger eras, and from the larger cycles to the smaller ones superimposed upon them.

As the book progresses from older to younger time scales, you will notice a change in the level of information about past climate changes. In part, this development reflects a change in the amount of detail that can be retrieved from climatic records, called the **resolution**. Because older records tend to have lower

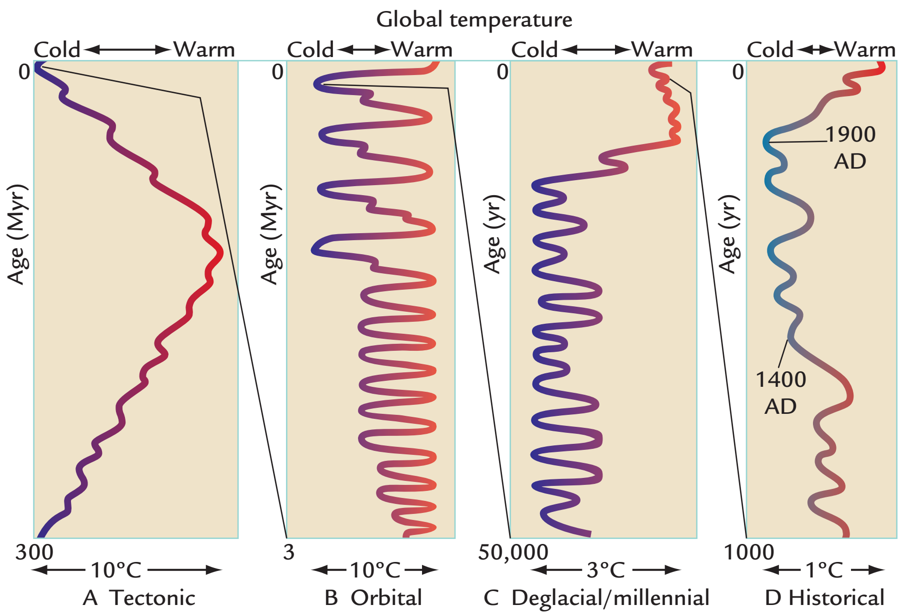


FIGURE 1-3

Time scales of climate change

Changes in Earth's climate span several time scales, arrayed from longer to shorter: (A) the last 300 million years, (B) the last 3 million years, (C) the last 50,000 years, and (D) the last 1,000 years. Here progressively smaller changes in climate at successively shorter time scales are magnified out from the larger changes at longer time scales.

resolution, much of the focus of Part II of this book is on the longer-term average climatic states over millions of years, and on the way they differ from our climate today. By comparison, younger records tend to have progressively higher resolution, and Parts III through V look at successively shorter-term changes in climate that occur within intervals of thousands, hundreds, and finally even tens of years. We will examine the resolution issue more closely in Chapter 3.

Development of Climate Science

As scientists began to discover examples of major climatic changes earlier in Earth's history, they were naturally curious about why these fluctuations happened. The few amateur scientists and university professors who studied climate in relative isolation during the nineteenth and early twentieth centuries have by now given way to thousands of researchers with backgrounds in geology, physics, chemistry, and biology working at universities, national laboratories, and research centers throughout the world (Figure 1-4). Today climate scientists use aircraft, ships, satellites, sophisticated new biological and chemical lab techniques, and high-powered computers, among other methods, to carry out their studies.

Studies of climate are incredibly wide-ranging. They vary according to the part of the climate system being studied, such as changes in air, water, vegetation, land surfaces, and ice. They also vary in the techniques used, including physical and chemical measurements of the properties of air, water, and ice and of life-forms fossilized in rocks; biological or botanical measurements of numerous kinds of life-forms; and computer simulations to model the behavior of air, water, and vegetation.

This huge diversity of studies covers a broad array of scientific disciplines. Some studies are directed at improving our understanding of the modern climate system: *meteorologists* study the circulation of the atmosphere; *oceanographers* explore the circulation of the ocean; *chemists* investigate the composition of the ocean, atmosphere, and land; *glaciologists* measure the behavior of ice; and *ecologists* analyze life-forms on land or in the water. Chapter 2 provides an overview of what we have learned about the operation of the climate system.

Other studies focus on changes in climate or climate-related phenomena in Earth's recent or more distant past: *geologists* explore the broader aspects of Earth's history; *geophysicists* investigate past changes in Earth's physical configuration (continents, oceans, and mountains); *geochemists* analyze past chemical changes in the ocean, air, or rocks; *paleoecologists* study past changes in vegetation and their role in the climate system; *climate modelers* evaluate possible causes of climate change; and *climate historians* explore written archives for information that will enable them to reconstruct past climates.

In recent decades, many studies of Earth's climatic history have crossed the traditional disciplinary boundaries and merged into an interdisciplinary approach referred to as "Earth system science" or "Earth system history." Such efforts recognize that the many parts of Earth's climate system are interconnected, and that investigators of climate must look at all of the parts in order to understand the whole. This book is an example of the **Earth system** approach.

In that regard, this book makes no special distinction between studies of Earth's past history and investigations of the current (or very recent) climatic record. Earth's climatic history is a continuum from

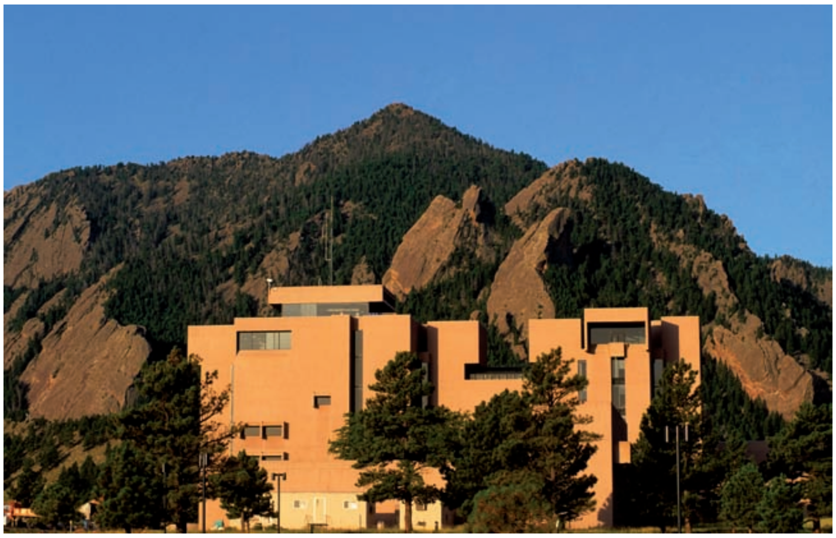


FIGURE 1-4
National research centers
The National Center for Atmospheric Research (NCAR) in Boulder, Colorado, is one of several national laboratories and university centers at which Earth's climate is studied. (SANDRA BAKER/ALAMY.)

the distant past to the present. The book is organized by time scale because that is the way Earth's climatic history has developed and will continue to develop in the future. Lessons learned about how the climate system has operated in the past can be applied directly to our understanding of the present and future, but the opposite is true as well. The broad term **climate science** refers to this vast *multidisciplinary* and *interdisciplinary* field of research, and to its linkage of the past, the present, and the future.

1-3 How Scientists Study Climate Change

Climate science moves forward by an interactive mix of observation and theory. Climate scientists gather and analyze data from the kinds of climatic archives reviewed in Chapter 3, and the results of this research are written up and published. Progress in science depends on the free exchange of ideas, and climate researchers publish in order to tell the scientific community what they have discovered.

Scientists who interpret their research results occasionally come up with a new **hypothesis** proposed to explain their observations. Other scientists evaluate these hypotheses, often discarding the ones that are less worthy because the predictions they make are contradicted by subsequent observations.

Any hypothesis that succeeds in explaining a wide array of observations over a period of time becomes a **theory**. Scientists continue to test theories by making additional observations, developing new techniques to analyze data, and devising models to simulate the operation of the climate system. Only a few theories survive years of repeated testing. These are sometimes called "unifying theories" and are generally regarded as close approximations to the "truth," but the testing continues.

Taken together, the many expanding efforts to understand climate change have led to a large-scale scientific revolution that has accelerated through the late 1900s and early 2000s. The mysteries of the climate system have yielded their secrets slowly, and many important questions still remain to be answered, but the revolution of knowledge to date has been immense, as this book will show.

This revolution has now expanded to a point where it is claiming a place alongside two great earlier revolutions of knowledge in Earth's history. The first was the development by Charles Darwin and others in the nineteenth century of the theory of **evolution**, which led to an understanding of the origin of the long sequence of life-forms that have appeared and disappeared during the history of this planet. The second was the synthesis during the 1960s and 1970s of the theory of **plate tectonics**, which has given us an understanding of the slow motions of the continents across Earth's surface through time, as well as associated phenomena such as volcanoes, earthquakes, and mountain ranges.

Overview of the Climate System

Earth's **climate system** consists of air, water, ice, land, and vegetation. At the most basic level, changes in these components through time are analyzed in terms of *cause* and *effect*, or, in the words used by climate scientists, **forcing** and **response**. The term "forcing" refers to those factors that drive or cause changes; the responses are the resulting climatic shifts.

1-4 Components of the Climate System

Figure 1-5 provides an initial (and simplified) impression of the vast array of factors involved in studying Earth's climate. It shows the air, water, ice, land, and

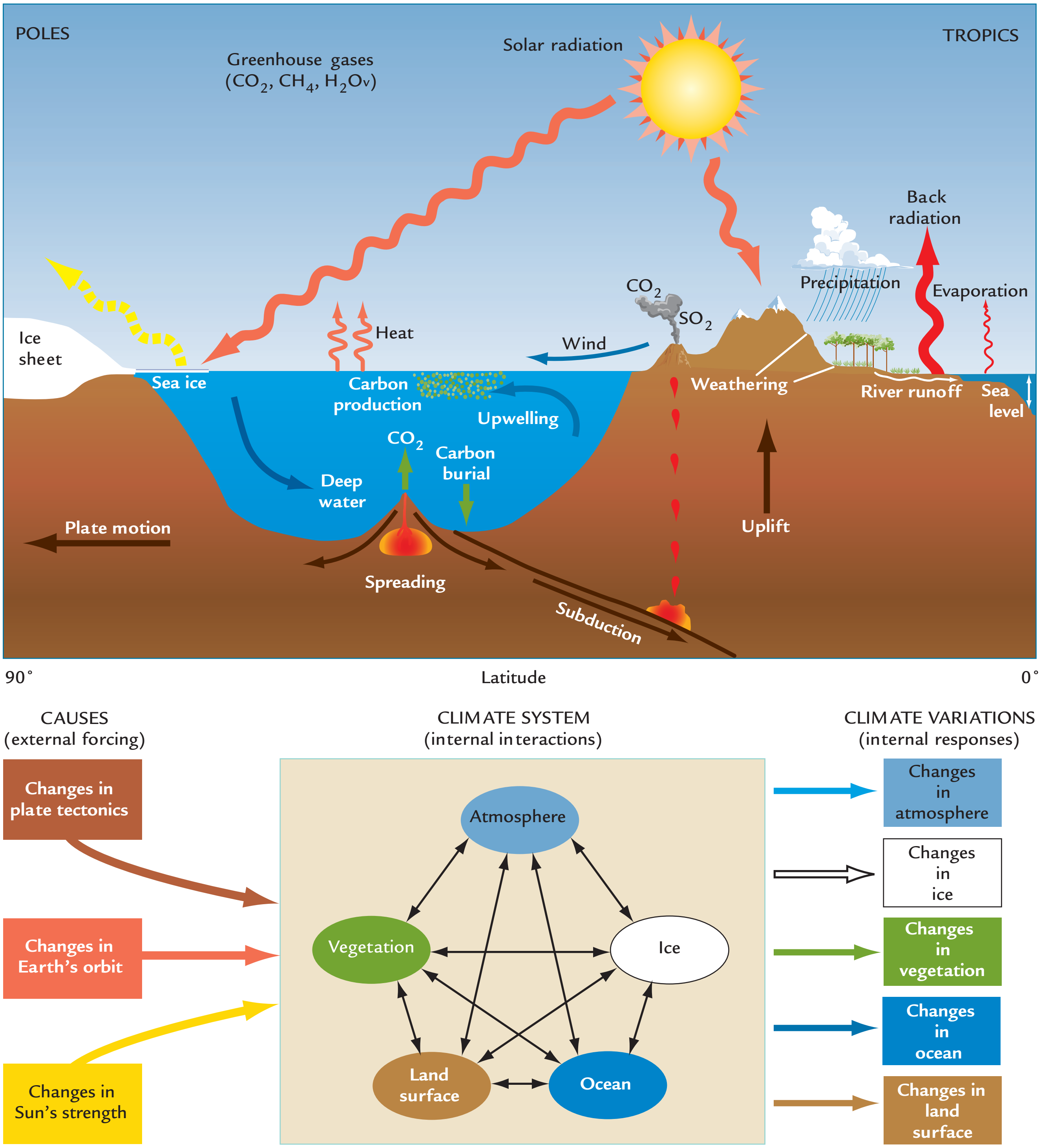


FIGURE 1-5

Earth's climate system and interactions of its components

Studies of Earth's climate cover a wide range of processes, indicated at the top. Climate scientists organize and simplify this complexity, as shown at the bottom. A small number of factors drive, or force, climate change. These factors cause interactions among the internal components of the climate system (air, water, ice, land surfaces, and vegetation). The results are the measurable variations known as climate responses.