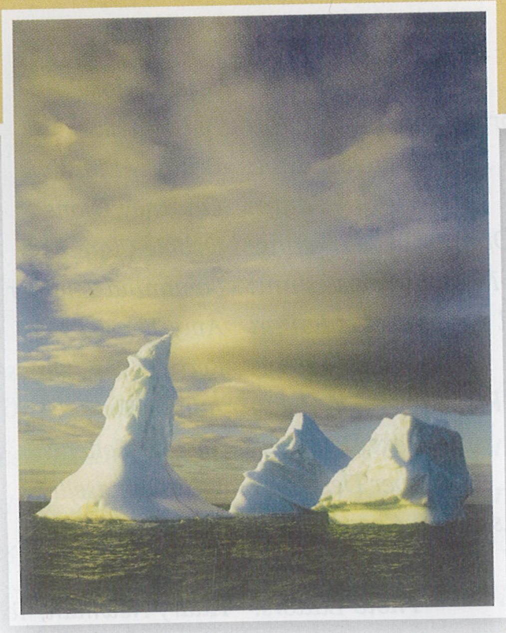

Earth's Climate

PAST AND FUTURE

Third Edition

WILLIAM F. RUDDIMAN

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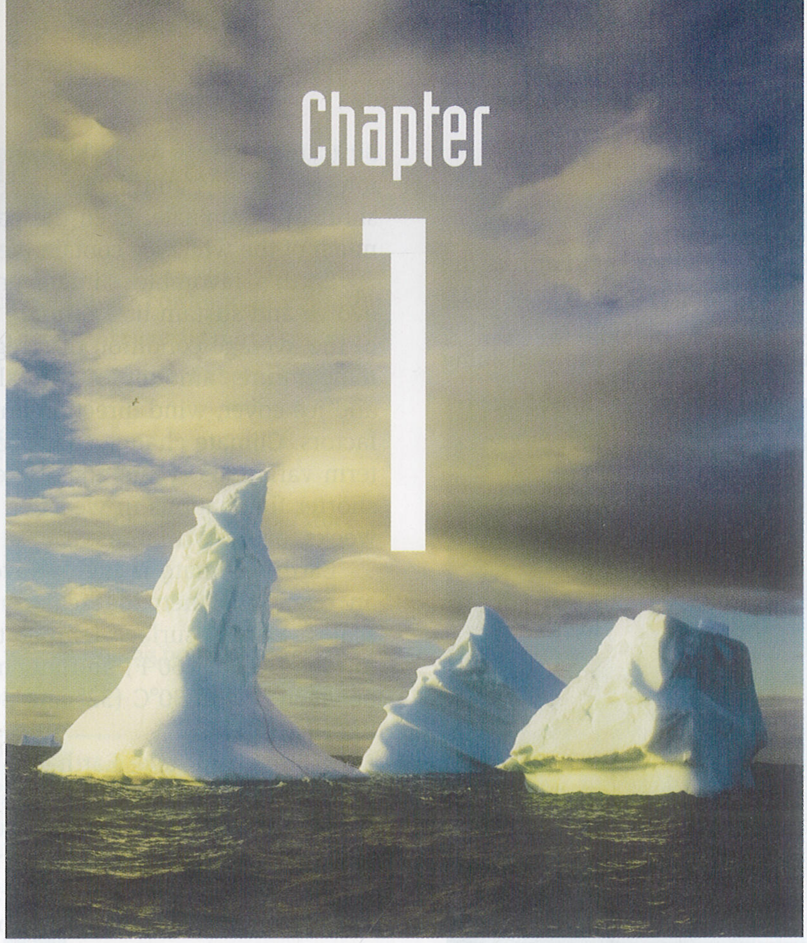
Chapter 1



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.

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.

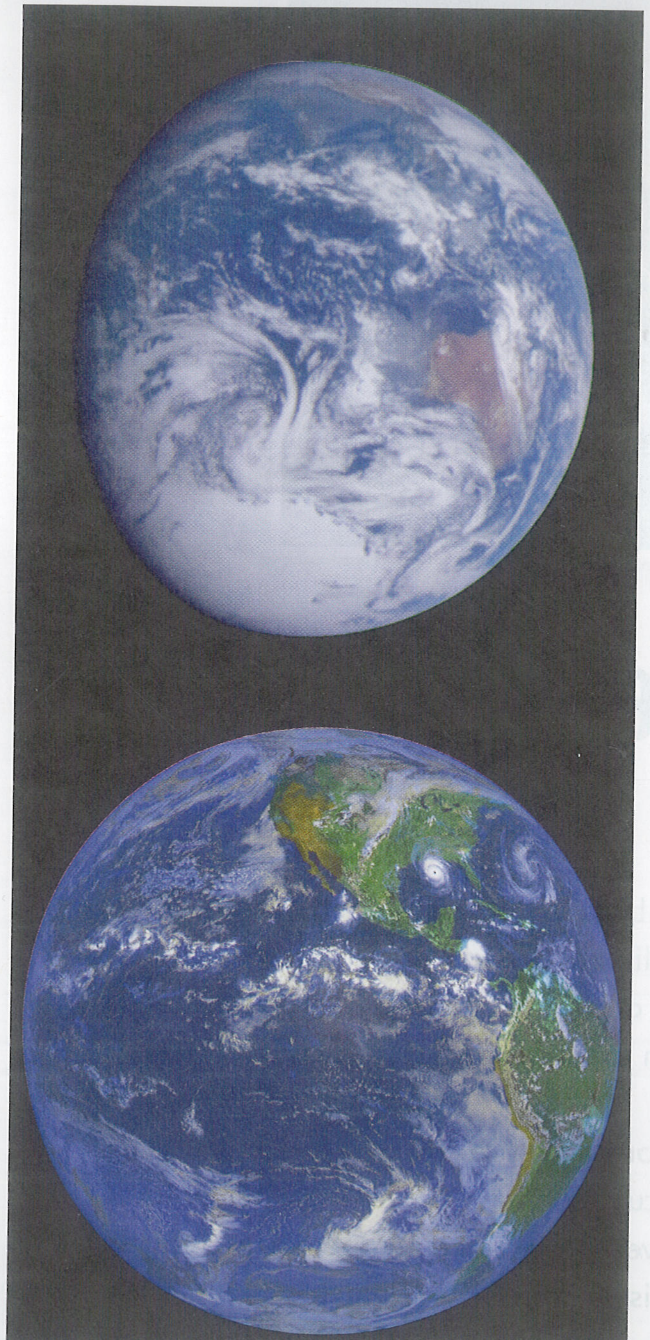


FIGURE 1-1
The habitable planet
Even seen from distant space, most of Earth's surface looks inviting to life, especially its blue oceans and green forests, but also its brown deserts and white ice. All these areas are prominent parts of Earth's climate system. (NASA.)

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.

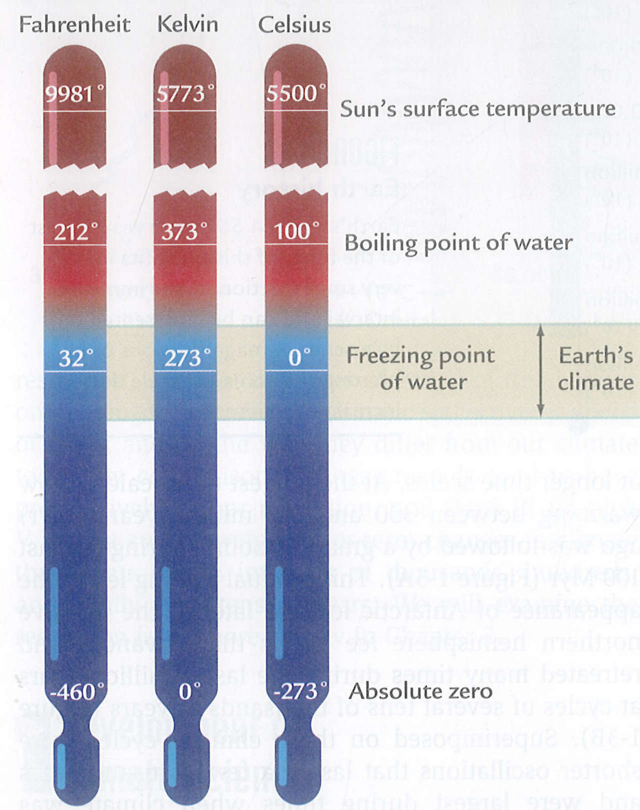
Almost all of Earth's long history lies immensely far beyond this human perspective. Earth formed 4.55 billion years (Byr) ago (4,550,000,000 years!). Most of the earliest part of Earth's history is known only in a sketchy way. One reason for this gap in our knowledge is the climate system itself: the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



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.)

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.

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

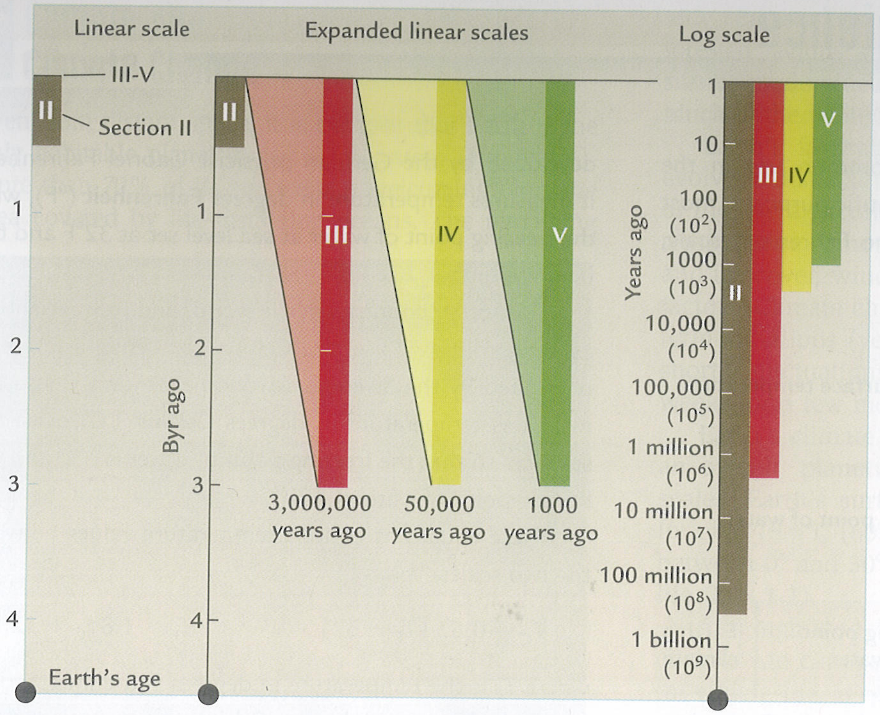


FIGURE 1-2
Earth history
Earth's age is 4.55 billion years. Most of the focus of this book fits into a very small fraction of this immense interval and can be represented only by a series of magnifications or by plotting time on a log scale that increases by factors of 10.

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

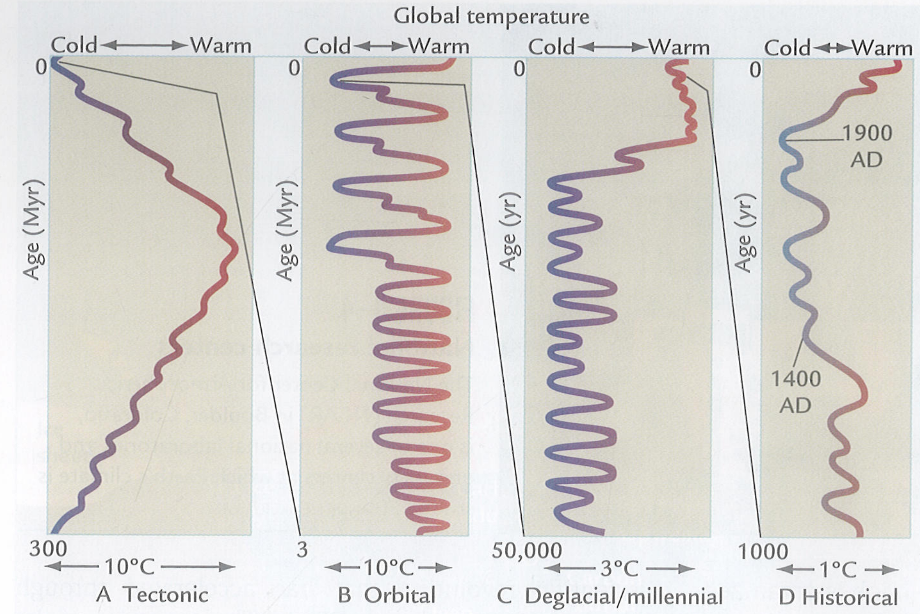


FIGURE 1-3
Time scales of climate change
Changes in Earth's climate span several time scales, arrayed from longer to shorter: (A) the last 300 million years, (B) the last 3 million years, (C) the last 50,000 years, and (D) the last 1,000 years. Here progressively smaller changes in climate at successively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

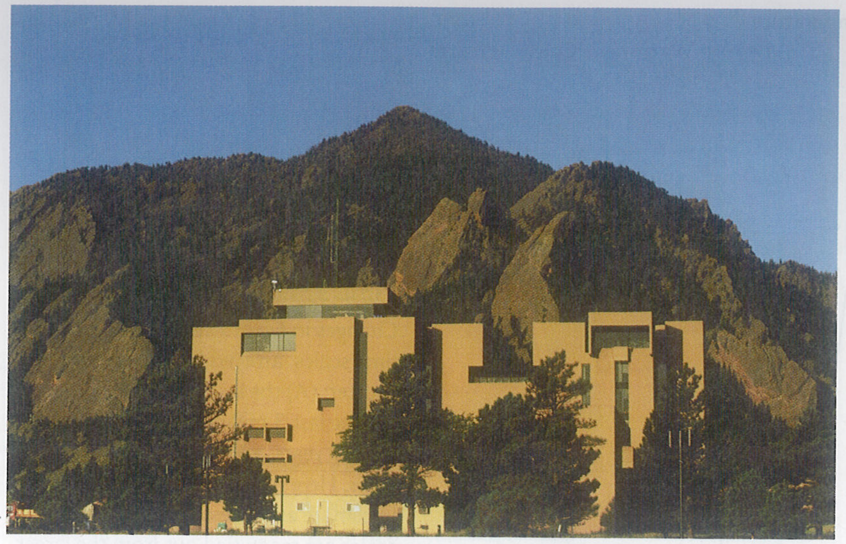


FIGURE 1-4
National research centers
The National Center for Atmospheric Research (NCAR) in Boulder, Colorado, is one of several national laboratories and university centers at which Earth's climate is studied. (SANDRA BAKER/ALAMY.)

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

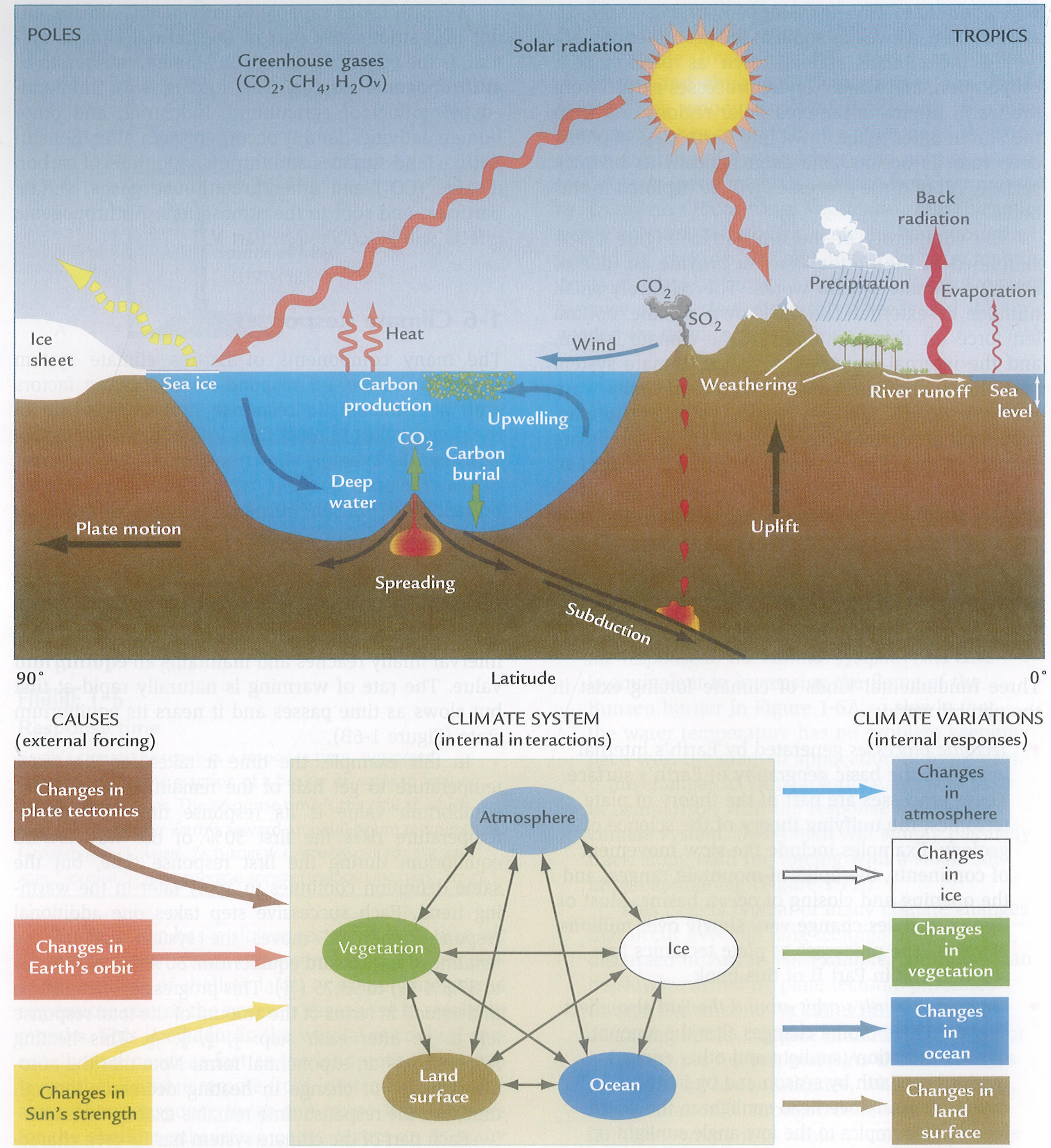


FIGURE 1-5
Earth's climate system and interactions of its components
Studies of Earth's climate cover a wide range of processes, indicated at the top. Climate scientists organize and simplify this complexity, as shown at the bottom. A small number of factors drive, or force, climate change. These factors 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.

vegetation that form the major components of the climate system, as well as some of the processes at work within the climate system, such as precipitation, evaporation, and winds. These processes extend from the warm tropics to the cold polar regions and from the Sun in outer space down into Earth's atmosphere, deep into its oceans, and even beneath its bedrock surface. All of these processes will be explored in this book.

The complexity of the top part of Figure 1-5 is simplified in the bottom part to provide an idea of how the climate system works. The relatively small number of external factors shown on the bottom left force (or drive) changes in the climate system, and the internal components of the climate system respond by changing and interacting in many ways (bottom center). The end result of all these interactions is a number of observed variations in climate (bottom right). This complexity can be thought of as the operation of a machine: the factors that drive climate change are the input, the climate system is the machine, and the variations in climate are the output.

1-5 Climate Forcing

Three fundamental kinds of climate forcing exist in the natural world:

- *Tectonic processes* generated by Earth's internal heat alter the basic geography of Earth's surface. These processes are part of the theory of plate tectonics, the unifying theory of the science of geology. Examples include the slow movement of continents, the uplift of mountain ranges, and the opening and closing of ocean basins. Most of these processes change very slowly over millions of years. The processes of plate tectonics are summarized in Part II of this book.
- *Changes in Earth's orbit around the Sun* also affect climate. These orbital changes alter the amount of solar **radiation** (sunlight and other energy) received on Earth by season and by latitude (from the nearly overhead sunlight in the warm low-latitude tropics to the low-angle sunlight or seasonal darkness at the cold high-latitude poles). Orbital changes occurring over tens to hundreds of thousands of years are the focus of Parts III and IV.
- *Changes in the strength of the Sun* also affect the amount of solar radiation arriving on Earth. One example appears in Chapter 5: the strength of the Sun has slowly increased throughout the 4.55 Byr of Earth's existence. In addition, shorter-term variations that occur over decades or longer are part of the focus of Part V.

A fourth factor capable of influencing climate, but not in a strict sense part of the natural climate system, is the effect of humans on climate, referred to as **anthropogenic forcing**. This forcing is an unintended by-product of agricultural, industrial, and other human activities, and it occurs through alterations of Earth's land surfaces and through additions of carbon dioxide (CO_2) and other **greenhouse gases**, sulfate particles, and soot to the atmosphere. Anthropogenic effects will be covered in Part V.

1-6 Climate Responses

The many components of Earth's climate system shown in Figure 1-5 respond to the driving factors with a characteristic **response time**, a measure of the time it takes to react fully to the imposed change. Consider the example shown in Figure 1-6A: a beaker of water placed above a typical laboratory Bunsen burner. The Bunsen burner represents an external climate forcing (such as the Sun's radiation), and the water temperature is the climatic response (such as the average temperature of Earth's surface). When the burner is turned on, it begins to heat the water. The water in the beaker gradually warms and after a long interval finally reaches and maintains an **equilibrium** value. The rate of warming is naturally rapid at first but slows as time passes and it nears its equilibrium state (Figure 1-6B).

In this example, the time it takes for the water temperature to get half of the remaining way to this equilibrium value is its response time. The water temperature rises the first 50% of the way toward equilibrium during the first response time, but the same definition continues to apply later in the warming trend. Each successive step takes one additional response time and moves the system half of the *remaining* way toward equilibrium: 50% ($\frac{1}{2}$) to 75% ($\frac{3}{4}$) to 87.5% ($\frac{7}{8}$) to 93.75 ($\frac{15}{16}$). This progression can also be understood in terms of the amount of the total response left to go after each step: $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$. This heating response has an exponential form. Note that the *absolute amount* of change in heating decreases through time, but the response time remains exactly the same.

Each part of the climate system has its own characteristic response time (Table 1-1), ranging from hours or days up to thousands of years. The atmosphere has a very fast response time, and significant changes can occur in just hours (as in daily cycles of heating and cooling). The land surface reacts more slowly, but it still shows large heating and cooling changes on time scales of hours to days to weeks. Beach sand can become too hot to walk on during a single summer afternoon, but it takes much longer to chill the upper layer of soil in winter to the point where it freezes.

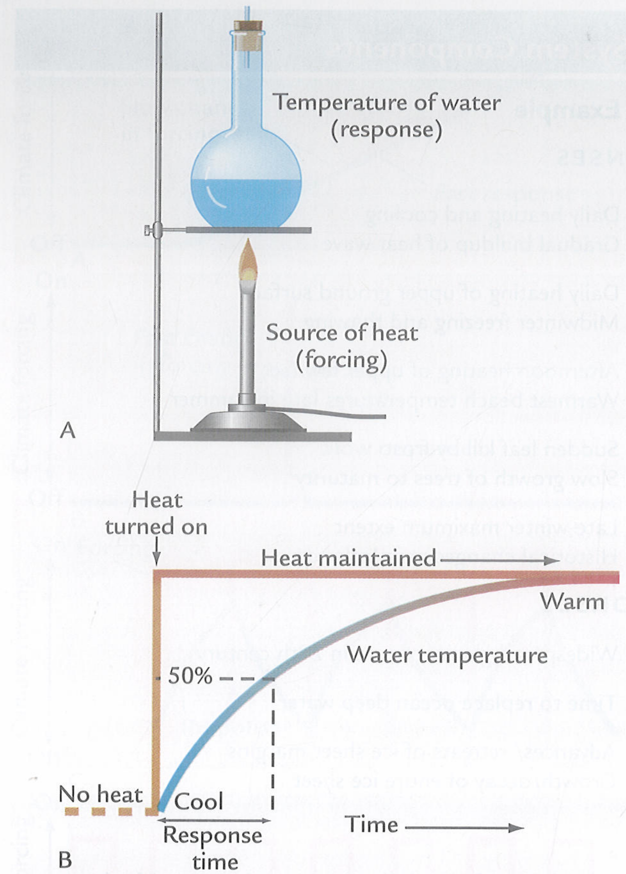


FIGURE 1-6
Response time
Earth's climate system has a response time, suggested conceptually by the reaction of a beaker of water to heating by a Bunsen burner. The response time is the rate at which water in the beaker warms toward an equilibrium temperature. (ADAPTED FROM J. IMBRIE, "A THEORETICAL FRAMEWORK FOR THE ICE AGES," *JOURNAL OF THE GEOLOGICAL SOCIETY* (LONDON) 142 [1985]: 417–32.)

Liquid water has a slower response time than air or land because it holds much more heat. The temperature response of shallow lakes or of the wind-stirred uppermost part of the ocean is measured in weeks to months. This is evident in the way lakes cool off seasonally, but never as fast as the land does. For ocean layers that lie more remote from interactions with the atmosphere, response times can range from decades for the shallow subsurface ocean layers up to many centuries for the deepest ocean.

Although a meter-thick layer of sea ice on polar oceans grows and melts in time periods ranging from months to years, thicker mountain glaciers react over longer time spans of decades or more. Massive (kilometers-thick) ice sheets like the one now covering the continent of Antarctica have the slowest response times in the climate system—many thousands of years, aptly captured in the familiar use of the word "glacial."

The response-time concept also applies to vegetation, an organic part of the climate system. Unseasonable frosts can kill leaves and grasses overnight, and abnormally hard freezes can do the same to the woody tissue of trees, with responses measured in just hours. On the other hand, seasonal spring greening of the landscape and normal autumn loss of leafy green material can take weeks or months to complete. Pioneering vegetation that occupies newly exposed ground (for example, bare ground left behind by melting glaciers) may take tens to hundreds of years or more to come to full development because of the slow dispersal of seeds and the time needed for them to germinate.

1-7 Time Scales of Forcing Versus Response

The parts of this book differ considerably in how the relationship between the forces that drive climate change and the responses of the climate system is treated. Several hypothetical cases shown in Figure 1-7 give a sense of these differences:

- *The forcing is very slow in comparison with the response of the climate system.* This case is equivalent to increasing the flame of the Bunsen burner in Figure 1-6A so slowly that the water temperature has no problem keeping pace with the gradual application of more heat. If the changes in climate forcing are very slow in comparison with the response time of the climate system, the system will simply passively track along with the forcing with a small but imperceptible lag (Figure 1-7A).

  This case is typical of many climate changes that occur over the long tectonic time scales discussed in Part II. For example, continents can be slowly carried by plate tectonic processes toward higher or lower latitudes at rates averaging about 1 degree of latitude (100 km or 60 miles) per million years. As the landmasses move toward lower latitudes, where incoming solar radiation is stronger, or toward higher latitudes, where it is weaker, temperatures over the continents will react to these slow changes in solar heating with imperceptibly tiny year-by-year responses. Because the response time of air over land is short (hours to weeks; see Table 1-1), the average temperature over the continents can easily keep pace with the slow changes in average overhead solar radiation over millions of years. Shorter-term changes also occur over tectonic time scales, but they are usually harder to resolve in older records.

Table 1-1 Response Times of Various Climate System Components

Component	Response Time (range)	Example
FAST RESPONSES		
Atmosphere	Hours to weeks	Daily heating and cooling Gradual buildup of heat wave
Land surface	Hours to months	Daily heating of upper ground surface Midwinter freezing and thawing
Ocean surface	Days to months	Afternoon heating of upper few feet Warmest beach temperatures late in summer
Vegetation	Hours to decades/centuries	Sudden leaf kill by frost Slow growth of trees to maturity
Sea ice	Weeks to years	Late-winter maximum extent Historical changes near Iceland
SLOW RESPONSES		
Mountain glaciers	10–100 years	Widespread glacier retreat in 20th century
Deep ocean	100–1,500 years	Time to replace ocean deep water
Ice sheets	100–10,000 years	Advances/ retreats of ice sheet margins Growth/decay of entire ice sheet

- *The forcing is fast in comparison with the climate system's response.* At the other extreme, the response time of the climate system may be far slower than the duration of the forcing (Figure 1-7B). In this case, little or no response to the climate forcing occurs. This case is equivalent to turning the Bunsen burner on and off so quickly that the temperature of the water in the beaker has very little time to react.

  One example of this extreme case is a total solar eclipse, which blocks Earth's only source of external heating for less than an hour. Air temperatures cool slightly during that brief interval, but then rise again. Volcanic eruptions are another example, such as the 1991 summer explosion of Mount Pinatubo in the Philippine Islands. Fine volcanic particles produced by that eruption blocked part of the Sun's radiation for several months and caused Earth's average temperature to fall by 0.5°C, but the cooling effect disappeared within a few years because fine volcanic particles only stay in the upper layers of the atmosphere for that long (Table 1-1).
- *The time scales of forcing and climate response are similar.* Between these two extremes is the more interesting case in which the time scales of the climate forcing and the climate system's responses fall within a similar range. This situation produces a more dynamic response of the climate system.

Consider a different experiment with the Bunsen burner and the beaker of water. This time, the Bunsen burner (again the source of climate forcing) is abruptly turned on, left on awhile, turned off, left off awhile, turned on again, and so on (Figure 1-7C). These changes cause the water to heat up, cool off, heat up again, and so on. The water temperature responds by cycling back and forth between two values, one toward the cold extreme with the flame off and one toward the warm extreme with the flame on. But the intervals of heating and cooling do not last long enough to allow the water time to reach either equilibrium temperature, as it did in the example shown in Figure 1-6B.

The difference between the two cases illustrated in Figures 1-7C and D shows that the frequency with which the flame is turned on and off determines the size of the water temperature response. Both examples assume the same equilibrium values (cold and warm) for the water temperature and the same position of the Bunsen burner relative to the beaker of water. The only difference in the forcing is the length of time the flame is left on or off. If the flame is switched on and off rapidly, the water temperature has less time to reach the equilibrium temperatures (hot or cold) and the size of the response is small (Figure 1-7D). But if the flame stays on or off for longer intervals, the temperature of the water has time to reach values closer to the full equilibrium states (Figure 1-7C).

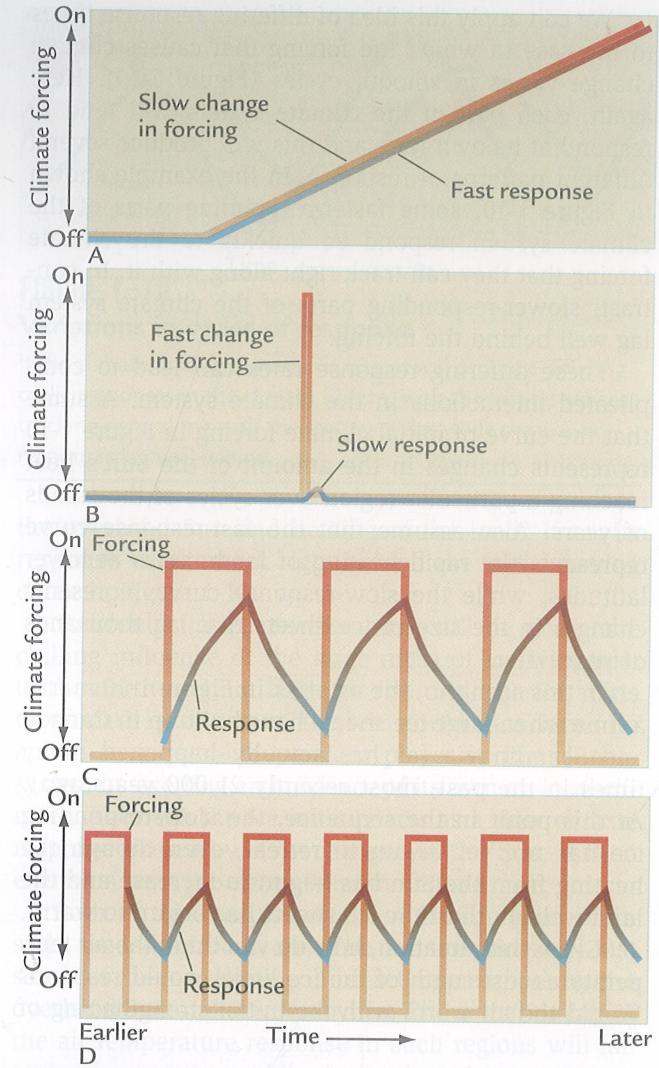


FIGURE 1-7
Rates of forcing vs. response
Climate responses depend on the relative rate of changes in climate forcing versus the response time of the climate system. (A) Very slow forcing may allow the climatic responses to track along with little delay. (B) Very fast changes in forcing may allow little reaction in slow climatic responses. (C, D) Roughly equal time scales of forcing and response allow varying amplitudes of response of the climate system.

In the real world, climate forcing rarely acts in the on-or-off way implied by the examples in Figure 1-7. Instead, changes commonly occur in smooth continuous cycles. If we again use the Bunsen burner concept, this situation is analogous to keeping the burner flame (the climate forcing) on at all times, but slowly and cyclically varying its intensity (Figure 1-8). The resulting cycles of warming and cooling of the water lag behind the shifts in the amount of heat applied, just as they did in Figure 1-7C and D.

Daily and seasonal changes provide familiar examples of this kind of forcing and response. In the Northern Hemisphere, the summer Sun is highest in the sky and therefore strongest at summer solstice on June 21, but the hottest air temperatures are not reached until July over the land and late August or early September over the ocean. Similarly, the coldest winter days occur over land in January or February, well after the weakest winter solstice Sun on December 21. Even during a single day, the strongest solar heating occurs near noon, but the warmest temperatures are not reached until the afternoon, hours later.

Even though the smooth cycles of forcing and response in Figure 1-8 look different from the cases examined in Figure 1-7, the underlying physical response of the beaker of water (or, by extension, of the climate system) remains exactly the same. The temperature of the water in the beaker continues to react at all times with the same characteristic response time defined earlier, and the rate of response of the climate system is once again fastest when the climate system is farthest from its equilibrium value.

The main difference now is that the climate forcing (the intensity of the flame from the Bunsen burner) is constantly changing, rather than holding at a single constant equilibrium value (as in Figure 1-6)

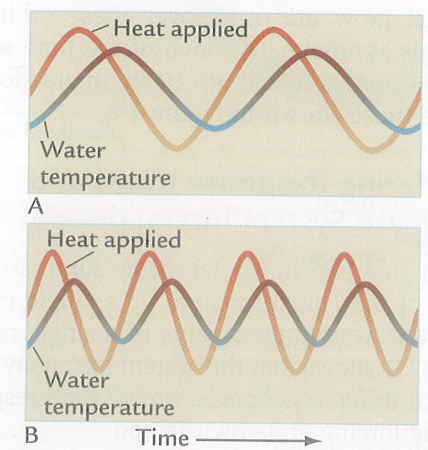


FIGURE 1-8
Cycles of forcing and response
Many kinds of climate forcing vary in a cyclical way and produce cyclic climate responses. The amplitude of the climate responses is related to the time they have to move toward equilibrium. (A) Climate changes are larger when the climate system has ample time to respond. (B) The same amplitude of forcing produces smaller climate changes if the climate system has less time to respond. (A AND B: ADAPTED FROM J. IMBRIE, "A THEORETICAL FRAMEWORK FOR THE ICE AGES," *JOURNAL OF THE GEOLOGICAL SOCIETY* (LONDON) 142 [1985]: 417–32.)

or switching between two equilibrium values in an alternating sequence (as in Figures 1-7C and D). These continuous changes in heating act as a "moving target." The climate system response (the water temperature) keeps chasing this moving target but can never catch up because the water temperature cannot respond quickly enough.

As was the case for the on-off changes shown in Figures 1-7C and D, the frequency with which these smooth cycles of forcing occur has a direct effect on the amplitude of the responses, an effect that is apparent in the differences between the cases shown in Figures 1-8A and B. If the forcing occurs in slower (longer) cycles, it produces a larger response (larger maxima and minima) because the climate system has more time to react before the forcing turns back in the opposite direction (see Figure 1-8A). In contrast, forcing that occurs in faster (shorter) cycles produces a smaller response because the climate system has less time to react before the forcing reverses direction (see Figure 1-8B). The two responses differ in size, even though the forcing moves back and forth between the same maximum and minimum values in both cases.

The relationships between forcing and response shown in Figure 1-8 are particularly useful for understanding the orbital-scale climatic changes explored in Parts III and IV of this book. Changes in incoming solar radiation due to changes in Earth's orbit occur over tens of thousands of years, and this also happens to be the response-time characteristic of the large ice sheets that grow and melt over these orbital time scales. This approximate match of the time scales of forcing and response sets up cyclic interactions very much like those shown in Figure 1-8.

1-8 Differing Response Rates and Climate System Interactions

The examples shown so far have summarized the response of the climate system by a single curve, as if the system were only capable of a single response. But Table 1-1 shows that the system has many components with different response times, each responding to climatic forcing at its own tempo.

One way to grasp the impact of these differences in response is to imagine that some change is abruptly imposed on the climate system from the outside (for example, a sudden strengthening of the Sun's radiation). Each part of the climate system will respond to this sudden increase in external heating in a way analogous to the beaker of water sitting over the Bunsen burner (Figure 1-6), but in this case at a tempo dictated by its own response time (Figure 1-9). The faster-responding parts of the climate system will warm up more quickly, and the slower-responding parts will do so more slowly.

We can apply this idea of differing response times to the case in which the forcing that causes climate change varies in smooth cycles (Figure 1-10). Here again, each part of the climate system will tend to respond at its own rate, and this will produce several different patterns of response. In the example shown in Figure 1-10, some faster-responding parts of the climate system respond so quickly to the climate forcing that they can track right along with it. In contrast, slower-responding parts of the climate system lag well behind the forcing.

These differing response rates can lead to complicated interactions in the climate system. Assume that the curve of initial climate forcing in Figure 1-10 represents changes in the amount of the Sun's heat reaching a particular region over cycles of thousands of years. Also assume that the fast-response curve represents the rapid heating of landmasses at lower latitudes, while the slow-response curve represents changes in the size of ice sheets that lag thousands of years later.

In this scenario, the asterisk in Figure 1-10 marks a time when large ice sheets have built up in Canada and Scandinavia (as has actually happened many times in the past, most recently 21,000 years ago). At this point in the sequence, the slow-responding ice has not yet begun to retreat, even though the heating from the Sun has begun to increase and the land well south of the ice sheets has begun to warm.

Given this situation, how do you think the air temperatures just south of the ice limits would respond? Would the air warm with the initial strengthening of

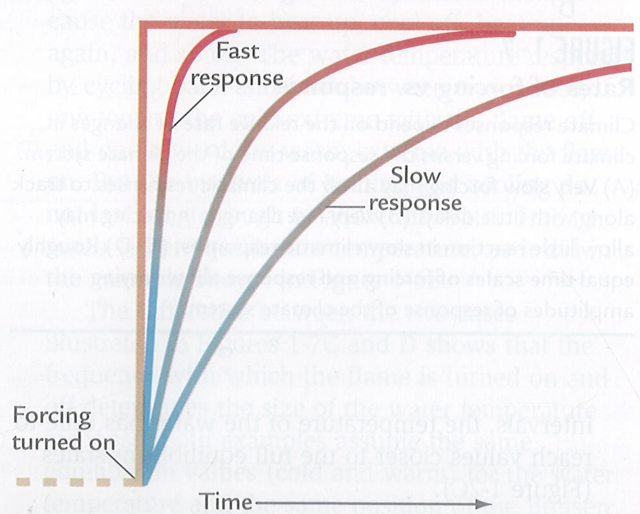


FIGURE 1-9
Variations in response times
An abrupt change in climate forcing will produce climate responses ranging from slow to fast within different components of the climate system, depending on their inherent response times.

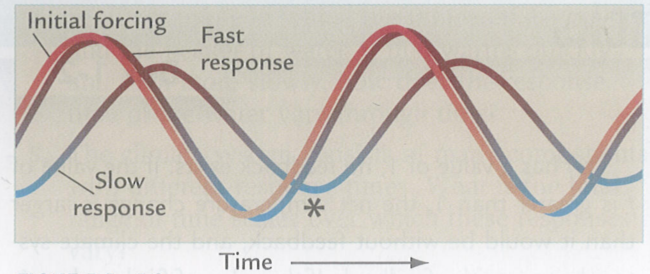


FIGURE 1-10
Variations in cycles of response
If the climate forcing occurs in cycles, it will produce differing cyclic responses in the climate system, with the fast responses tracking right along with the forcing cycles while the slower responses lag well behind.

the overhead Sun and heating of the land? If so, its response would track right behind the initial forcing curve in Figure 1-10.

Or would the air temperatures still be under the chilling influence of the large mass of ice lying just to the north and not begin to rise until the ice starts to retreat? In this case, the ice would in a sense be acting as a semi-independent player in the climate system by exerting an influence of its own on local climate. Although the ice initially acts as a slow climate response driven by slow changes in the Sun, it then exerts its own separate effect on climate.

Both of these explanations probably sound plausible, and they both are. The air temperatures just south of the ice sheets will be influenced *both* by the overhead Sun and the nearby ice. The actual timing of the air temperature response in such regions will fall somewhere in the middle, faster than the response of the ice but lagging behind the forcing from the Sun. As this example suggests, Earth's climate system is dynamic, with numerous interactions.

The response-time concept is directly relevant to projections of climate change in the near future. Part V of this book addresses the effects of humans on climate through the buildup of greenhouse gases, primarily CO_2 produced from burning fossil fuels (coal, oil, and natural gas). The changes in the next few centuries will be unusual because the large climate forcing caused by humans and the warming it will bring will arrive at a speed much faster than the large changes known from Earth's history. Within a few centuries, the fossil fuels that generate excess CO_2 in the atmosphere will be largely used up, CO_2 emissions will fall, and Earth's climate will begin to return toward its previous cooler state. But before that happens, Earth will face centuries of very substantial warmth, along with many other changes.

Scientists, and the public in general, want to know how large the disruption caused by these oncoming centuries of very high CO_2 concentrations will be, and the answer to this question requires understanding the different response times of the major components in the climate system. Most parts of the system will begin to respond relatively quickly to the greenhouse-gas forcing, but others (those most closely tied to the ice sheets and deep ocean) will respond more sluggishly. A large part of the challenge facing climate scientists is to sort out these different responses and all their interactions.

1-9 Feedbacks in the Climate System

Another important kind of interaction in the climate system is the operation of **feedbacks**, processes that alter climate changes that are already underway, either by amplifying them (**positive feedbacks**) or by suppressing them (**negative feedbacks**). Figure 1-11 shows how feedbacks operate.

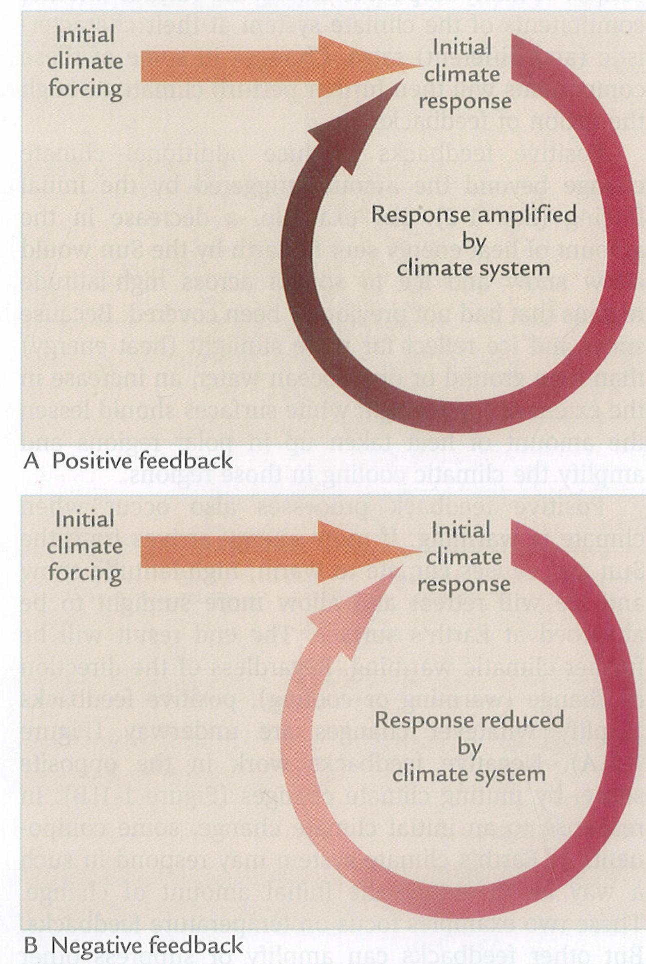


FIGURE 1-11
Climate feedbacks
(A) Positive feedbacks within the climate system amplify climate changes initially caused by external factors. (B) Negative feedbacks mute or suppress the initial changes.

Climate Interactions and Feedbacks

Box 1-2

Positive and Negative Feedbacks

The strength of a feedback on temperature, called the **feedback factor**, or f, is defined as:

$$f = \frac{\text{temperature change with feedback}}{\text{temperature change without feedback}}$$

where "temperature change" refers to the full equilibrium response

If f has a value of 1, no feedback exists. If the value of f is greater than 1, the net temperature change is larger than it would be without feedback, and the climate system has a positive feedback. If the value of f is less than 1, the temperature change is smaller than it would be in the absence of feedback, and the climate system has a negative feedback.

Assume that some external factor (again, perhaps a change in the strength of radiation from the Sun) causes Earth's climate to change. Those changes will consist of many responses among the various internal components of the climate system at their characteristic (and different) rates. Changes in some of these components will then further perturb climate through the action of feedbacks.

Positive feedbacks produce additional climate change beyond the amount triggered by the initial forcing (Box 1-2). For example, a decrease in the amount of heat energy sent to Earth by the Sun would allow snow and ice to spread across high-latitude regions that had not previously been covered. Because snow and ice reflect far more sunlight (heat energy) than bare ground or open ocean water, an increase in the extent of these bright white surfaces should lessen the amount of heat taken up in polar regions and amplify the climatic cooling in those regions.

Positive feedback processes also occur when climate is warming. If more energy arrives from the Sun and causes climate to warm, high-latitude snow and ice will retreat and allow more sunlight to be absorbed at Earth's surface. The end result will be further climatic warming. Regardless of the direction of change (warming or cooling), positive feedbacks amplify whatever changes are underway (Figure 1-11A). Negative feedbacks work in the opposite sense, by muting climate changes (Figure 1-11B). In response to an initial climate change, some components of Earth's climate system may respond in such a way as to reduce the initial amount of change. These two examples focus on temperature feedbacks. But other feedbacks can amplify or suppress other climatic responses, such as precipitation.

In Summary, the climate system is highly complex and can seem (to someone new to this subject) daunting. But an age-old wisdom suggests that seemingly insurmountable problems can be understood if they are broken down into smaller ("bite-sized") pieces. This book tries to simplify that complexity by first organizing climatic changes by time scale, and then exploring the most important climatic drivers (forcings) and responses, including of the interactions and feedbacks among the responses.

Key Terms

climate (p. 4)
weather (p. 4)
Fahrenheit (p. 5)
Celsius (p. 5)
Kelvin (p. 5)
resolution (p. 6)
Earth system (p. 7)
climate science (p. 8)
hypothesis (p. 8)
theory (p. 8)
evolution (p. 8)
plate tectonics (p. 8)
climate system (p. 8)
forcing (p. 8)
response (p. 8)
radiation (p. 10)
anthropogenic forcing (p. 10)
greenhouse gases (p. 10)
response time (p. 10)
equilibrium (p. 10)
feedbacks (p. 15)
positive feedback (p. 15)
negative feedback (p. 15)
feedback factor (p. 16)

Review Questions

1. How does climate differ from weather?
2. In what ways does climate science differ from traditional sciences such as chemistry and biology?
3. How does climate forcing differ from climate response?