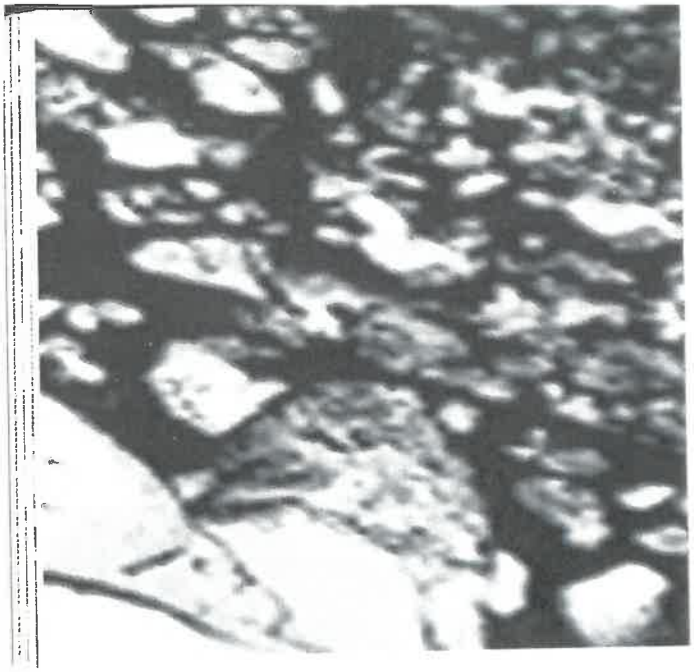


CHAPTER 14

Pleistocene Glaciations

Key Questions

- What has caused Earth to oscillate in and out of glacial states over the past 2 million years?
- What geologic evidence substantiates theories about the causes of glaciation?
- How are glacial-to-interglacial cycles related to changes in Earth's orbit?
- Have components of the Earth system amplified the glacial climate response?
- What caused the abrupt and brief return to the glacial state after the latest deglaciation?

Chapter Overview

When viewed on multimillion-year time scales, Earth is presently in a glacial interval. Thick continental ice sheets cover Antarctica and Greenland, and only 20,000 years ago vast portions of northern North America and Scandinavia and other parts of northern Europe and Asia were covered with accumulations of ice that were many kilometers thick. Although polar ice has existed on Antarctica for tens of millions of years, only during the past 2.5 million years have ice sheets extended from the Arctic into the northern midlatitudes. Thus, there is something peculiar about the operation of Earth's climate system during the past 2.5 million years that distinguishes it from the rest of the past 300 million years of Earth history.

In addition, there is now convincing evidence that this glacial interval, known as the **Pleistocene epoch** (1.8 million years ago to about 12,000 years ago), was characterized by regular cycles of growth and decay of Northern Hemisphere continental ice sheets. The oscillations are likely to continue. The warmer interval we are enjoying now, known as the **Holocene epoch**, would under natural conditions end several thousand years from now as the Northern Hemisphere ice sheets return. Continued burning of fossil fuels may, however, forestall or even prevent this transition to the glacial state. What causes this cyclicity of glaciation?

As we will see, changes both in the distribution of sunlight across Earth's surface (insolation) and in atmospheric CO_2 seem to be involved. These changes in insolation are a predictable feature of Earth's orbit about the Sun—during warm as well as cold intervals of Earth history. They were not discussed in Chapter 12 because the magnitude of the forcing is small compared with that of the changes brought about by solar evolution on 100-million-year time scales. Yet as we narrow our focus to shorter time scales of climate change, these more subtle forcings increase in importance. During the Mesozoic, orbital changes caused cyclical variations in sedimentation that likely reflect climate change. But the Pleistocene climate system seems to have been especially attuned to these forcings, as indicated by the large oscillations of continental ice sheets.

GEOLOGIC EVIDENCE OF PLEISTOCENE GLACIATION

The scenic beauty of Canada and the northern portions of the United States, Asia, and Europe is to a great extent the result of the action of tremendously large sheets of ice that covered these regions during the Pleistocene epoch (Figure 14-1). Buried under more than a kilometer of ice, the land surface was plucked, ground up, and excavated. With the melting of the ice, the depressions formed in this way were filled with water and became the thousands of lakes that pepper the North country. In this section we will see that the modification of the landscape by glaciers, together with their effect on the isotopic composition of seawater, provide convincing evidence that continental ice sheets expanded and decayed several times during the Pleistocene with almost clockwork regularity.

Glacial Deposits Document Major Glaciations

As we saw in Chapter 12, several types of geological features are characteristic of glaciation. As glaciers advance, rocks frozen to their base gouge the bedrock below. These gouges, called **glacial striations** (Figure 14-2a), indicate the direction of past glacial movement. The advance of continental ice sheets modifies the landscape in other ways as well. Ridges of sediment, known as **moraines** (Figure 14-2b), are deposited at the front and sides of the ice sheets. When the ice melts, these ridges are left behind, marking the farthest advance of the ice sheet. The indiscriminate nature of glacial erosion and deposition is reflected in the sediment contained in moraines and other glacial deposits. This sediment, called **till** (Figure 14-2c), contains a mixture of material of various sizes, from mud to boulder-sized rocks, and various composition, reflecting rocks eroded from a variety of places and transported to the point of deposition by the advancing ice sheet. Some of the material produced by glacial abrasion is silt-sized (about hundredths of a millimeter in diameter). When deposited in the typically arid region that surrounds continental ice sheets, this material is picked up by the wind and carried great distances. Such windblown deposits, known as **loess** (Figure 14-2d), form the rich soils of the midwestern U.S. grain belt.

Geologists of the 19th century used glacial deposits, including the geographical distribution of moraines, to define four main intervals of glaciation in Europe, from oldest to youngest: the Gunz, the Mindel, the Riss, and the Würm. In the early part of the 20th century, four glaciations were also identified in North America, from oldest to youngest: the Nebraskan, the Kansan, the Illinoian, and the Wisconsinan. These glaciations on separate continents are now known to have been coincident with each other, and they represent the largest of the glacial episodes. Ice sheets in the Northern Hemisphere were advancing and retreating in unison. But the number four greatly underestimates how often this process has occurred. The problem is that each successive advance obliterates much of the geological record of earlier advances.

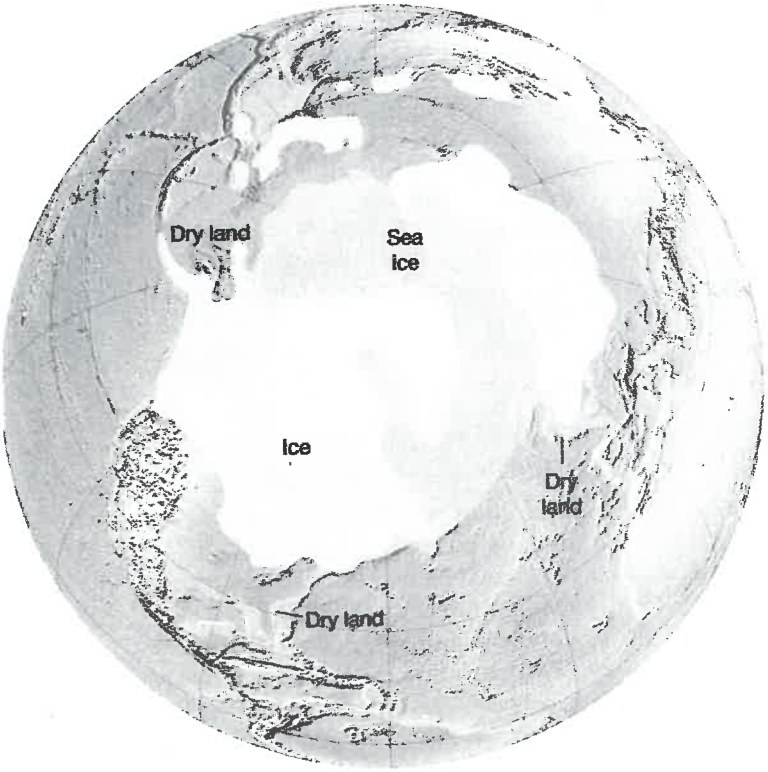


FIGURE 14-1 The Pleistocene ice sheet at maximum extent. (*Source:* From W. K. Hamblin and E. H. Christiansen, *Earth's Dynamic Systems*, 8/e, 1998. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

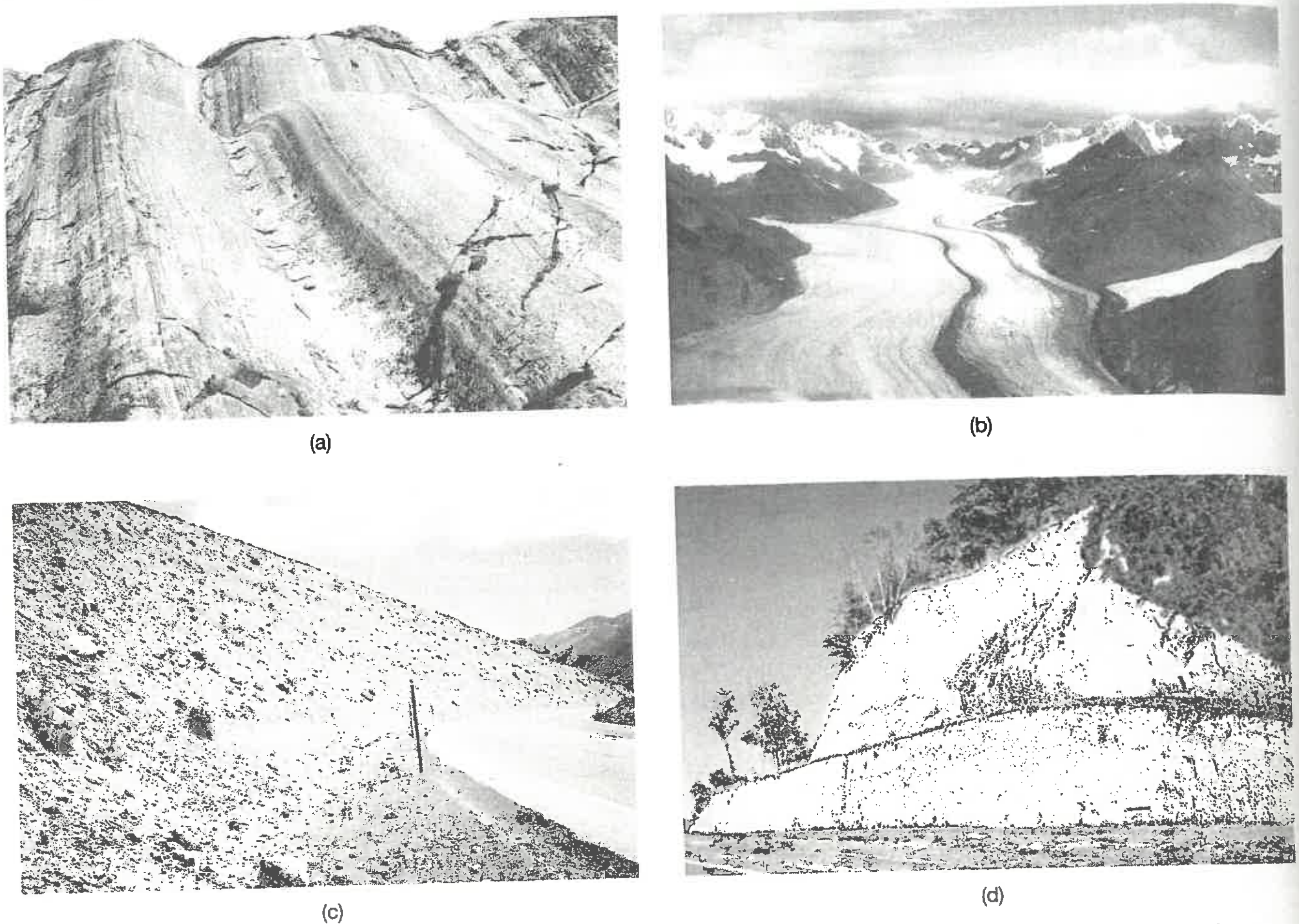


FIGURE 14-2 Various geological features characteristic of glaciation. (a) Glacial striations are formed by the gouging out of bedrock by pebbles frozen onto the base of an advancing glacier. The lineations indicate the direction of glacial movement. (b) Moraines form by the bulldozing action of advancing glaciers. (c) Till is the mix of sediments of various types and sizes resulting from the indiscriminate transportation by glaciers. (d) Loess is fine-grained sediment produced by glacial abrasion and transported to the site of deposition by wind. (*Sources:* (a) Walter H. Hodge/Peter Arnold and (b), (c), (d) TLM Photo.)

Detailed analysis of layers upon layers of wind-blown loess, preserved throughout Europe, proved that there had been at least 17 glacial intervals prior to the last. And evidence from marine sediments, described next, showed that such cycles have occurred with clocklike regularity for more than 2.5 million years.

The Oxygen Isotope Record of Glacial–Interglacial Oscillations

While ice sheets were destroying the sedimentary record of glaciation on land, a continuous record of climate change was being deposited on the seafloor. This record, however, was chemical rather than physical; it was contained in the isotopic composition of the skeletons of marine organisms. The ratio of the stable isotopes ^{18}O and ^{16}O in the calcium carbonate skeletons of marine plankton depends on the temperature of that water. The colder the water, the greater the tendency for minerals to incorporate ^{18}O, and thus the larger the ratio of ^{18}O to ^{16}O in $CaCO_3$. Oxygen isotope ratios are typically reported in "delta" notation, where (^{18}O is the ratio of ^{18}O to ^{16}O normalized to a standard (either seawater or a standard limestone) and multiplied by 1000 to accentuate the small differences observed. (See Chapter 5 for further discussion of isotopes.)

Theoretically, then, the isotopic analysis of skeletal material recovered from cores of deep-sea sediments should reveal the history of temperature fluctuations in the overlying surface waters. However, an additional isotopic effect is equally important. As continental ice sheets grow, significant quantities of water are removed from the oceans (Figure 14-3). Aside from causing considerable drops in sea level (the last glaciation dropped sea level by about 120 m), significant changes in the oxygen isotopic composition of seawater occur as well. Evaporation transfers both $H_2{}^{16}O$ and $H_2{}^{18}O$ from the ocean to the atmosphere, but there is a preferential release of $H_2{}^{16}O$ to the vapor phase. Moreover, water-vapor molecules containing ^{18}O tend to condense more readily than do those containing ^{16}O, the lighter

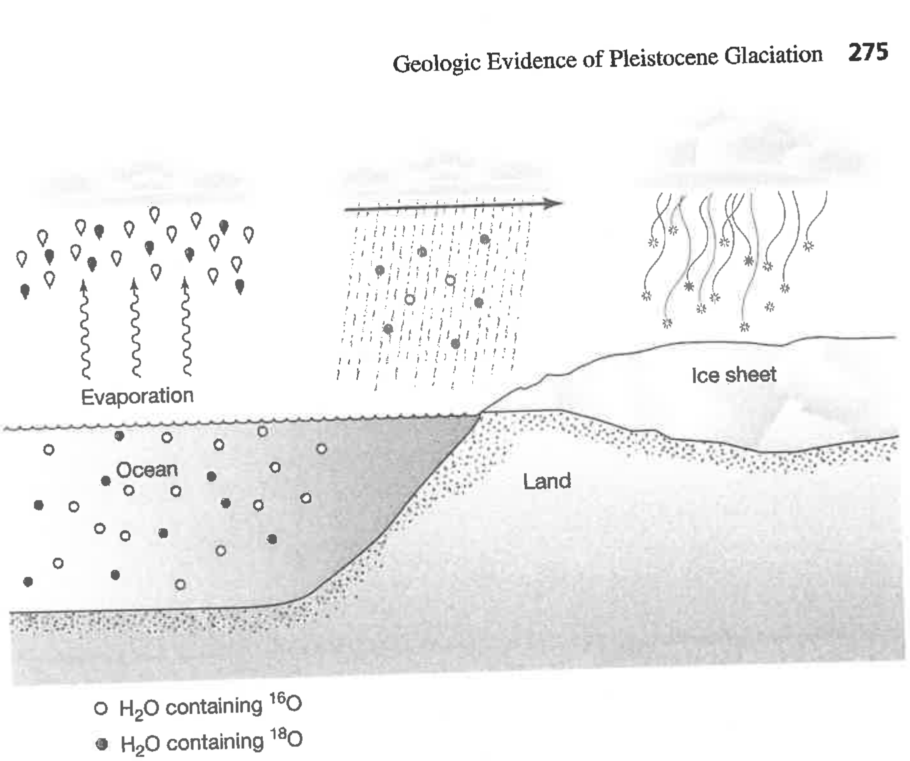


FIGURE 14-3 Changes in the oxygen isotopic composition of seawater during the growth of continental ice sheets.

isotope. Thus, rain falling from the atmosphere preferentially removes ^{18}O, leaving the residual water vapor further enriched in ^{16}O. Snow falling onto the ice caps has traveled considerable distances and has had its ^{16}O content considerably enriched. The net preferential removal of ^{16}O from the oceans to ice sheets increases the $\delta^{18}O$ of the oceans. This effect adds to the direct temperature effect: Calcium carbonate precipitated from a glacial-age ocean has a larger $\delta^{18}O$, both because the water is cold and because the seawater is enriched in the heavier isotope.

In the 1950s the first deep-sea sediment cores were recovered, and isotopic analyses were performed on them. Instead of the four glaciations originally indicated by the continental record, the marine record indicated that dozens of climate swings have occurred over the course of the Pleistocene (Figure 14-4). The major intervals of Northern Hemisphere glaciation—**glacials**—of the past 700,000 years appear to have occurred every 100,000 years or so. During glacials, the globally averaged surface temperature was about 9–10°C (about 5–6°C cooler than today) and atmospheric CO_2 concentrations were about 200 ppm. These cold intervals are separated by warmer, shorter intervals known as **interglacials**. During interglacials, continental glaciation is limited to Greenland and Antarctica; globally averaged surface temperatures are about 15°C and atmospheric CO_2 concentrations are about 280 ppm. The Holocene epoch (the past 10,000 years) represents one such interglacial.

The regularity of glacial–interglacial variation is remarkable. The **period** of a cyclical phenomenon is the time it takes to complete one cycle. Curiously, the dominant periodicity (cyclical nature) of glacial–interglacial variation seems to have been different prior to 700,000 years ago. Before that time, glacial–interglacial swings were smaller and occurred on approximately a 40,000-year time scale. Something fundamental to the climate system changed 700,000 years ago, and scientists are actively working to resolve what that fundamental change was. The pre-Pleistocene cooling and the onset of significant continental glaciation in the Northern Hemisphere

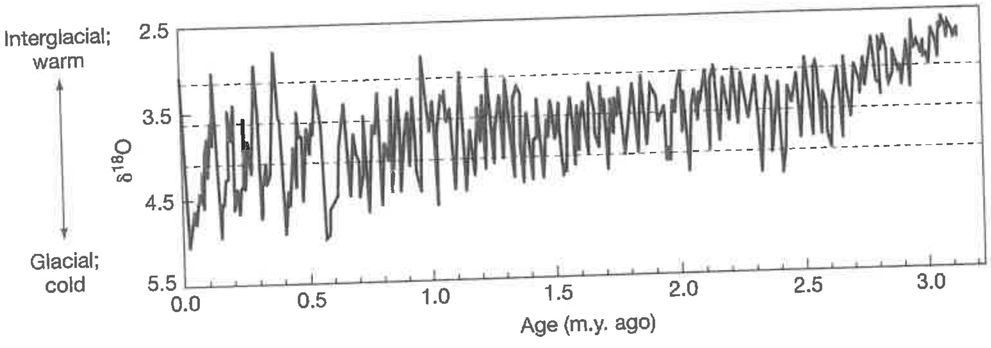


FIGURE 14-4 Deep-sea record of the $\delta^{18}O$ of seawater during the Pleistocene epoch. The analyses were performed on two genera of bottom-dwelling foraminifera deposited in the sediments of the midlatitude North Atlantic. Interglacials appear as peaks, with smaller values of $\delta^{18}O$; glaciations appear as valleys. Note that time proceeds forward to the left. (*Source:* M. E. Raymo, *Annual Review of Earth and Planetary Sciences* 22, 1994, pp. 353–383.)

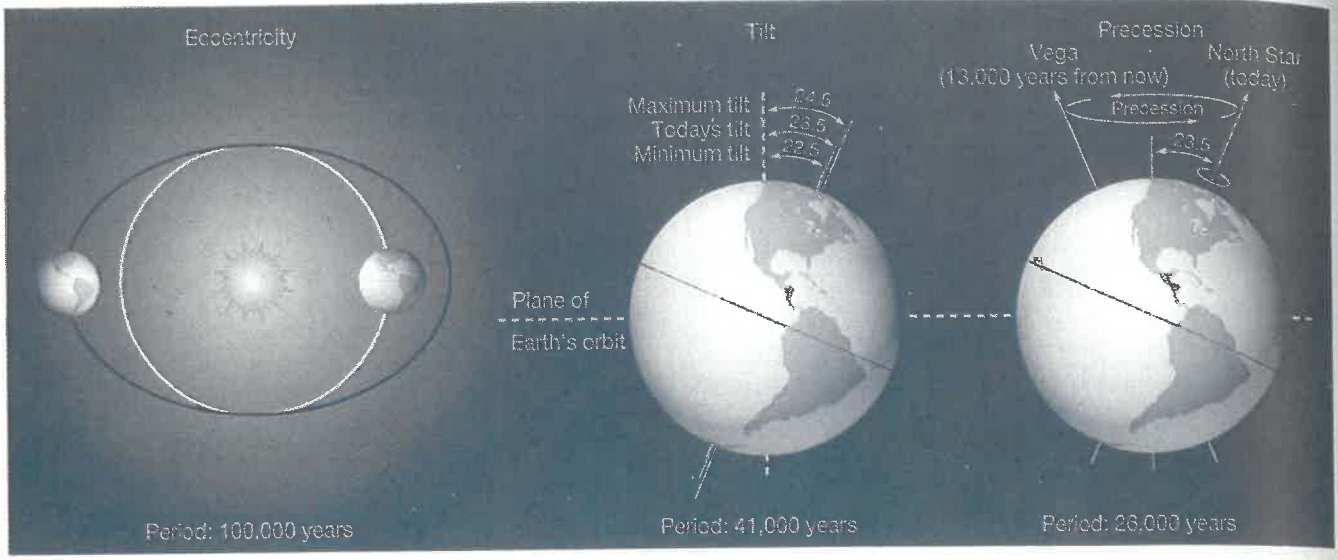


FIGURE 14-5 Aspects of Earth's orbit around the Sun that have implications for climate change. (a) The elliptical nature of the orbit (eccentricity) changes on 100,000- and 400,000-year time scales. (b) The tilt of the spin axis with respect to the plane of Earth's orbit around the Sun (obliquity) changes on a 41,000-year time scale. (c) The orientation of the spin axis in space wobbles (precesses) with a 26,000-year period. (*Source:* From J. P. Davidson, W. E. Reed, and P. M. Davis, *Exploring Earth: An Introduction to Physical Geology*, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

(from 3.0 to 2.5 million years ago) are also apparent in the oxygen isotope record (see Figure 14-4).

Why has Earth's climate system been oscillating between these two states—glacial and interglacial—with apparent periods of 100,000 and 40,000 years? The answer seems to involve small changes in the way Earth orbits the Sun, changes that repeat in a predictable fashion over tens of thousands of years. Three sorts of changes are involved (Figure 14-5):

1. changes in the degree to which Earth's orbit around the Sun is elliptical (eccentricity);
2. changes in the tilt of Earth's spin axis with respect to the plane of its orbit around the Sun (obliquity); and
3. changes in the orientation of the spin axis with respect to Earth's orbit (precession).

The pacemaker that determines the variability of climate requires amplification, especially for the 100,000-year climate cycles, because only small changes in annual-average insolation result from eccentricity variations. We will first explore these orbital variations and will compare their predictions to the isotopic record from deep-sea sediment cores. We then discuss feedback mechanisms (including those affecting atmospheric CO_2) that may have provided the amplification necessary to create the large climate swings of the Pleistocene.

MILANKOVITCH CYCLES

What causes these remarkably regular shifts in Earth's climate? Long before the oxygen isotope evidence was obtained, scientists of the 19th century had suspected that the Pleistocene glacial–interglacial cycles were caused by variations in Earth's orbit around the Sun. In the early part of the 20th century, this hypothesis was put on a quantitative footing by the Serbian mathematician Milutin Milankovitch. He not only elaborated the mathematical theory of how orbital variations affect climate, but also calculated the changes in orbital parameters over the past several thousand years and demonstrated the connection between this theory and the rather scant geological record that existed during his time. The regular variations in Earth's orbit are often referred to as *Milankovitch cycles* in honor of this achievement. Milankovitch suggested that the critical factor for Northern Hemisphere continental glaciation was the amount of summertime insolation at high northern latitudes. High insolation leads to warmer summers, and the winter snowpack melts (as we see today). However, under low insolation the snowpack would survive over the summer, allowing snow and ice to accumulate and an ice sheet to form. Subsequent summers would allow further growth of the ice sheet toward lower latitudes.

Despite the elegance of Milankovitch's "astronomical theory of the Ice Age," it was strongly criticized by the scientific community in the 1920s and 1930s, in part because the available geologic record did not support the hypothesis of many Pleistocene glaciations. His response to these criticisms is perhaps best reflected in this excerpt from his 1941 book: "I do not consider it my duty to give an elementary education to the ignorant, and I have also never tried to force others to apply my theory, with which no one could find fault." Given the rather limited amount of tact with which Milankovitch presented his theory of the Ice Ages, it is not surprising that his brilliance was not widely acknowledged until well after his death.

Orbital Theory

Orbital theory itself predates Milankovitch; the fundamentals of this theory were developed in the 17th century by Johannes Kepler and Isaac Newton. The results are summarized by three rules that are known as *Kepler's laws* (see the Box "Thinking Quantitatively: Kepler's Laws"). The most important of these laws for our purposes is the first: The planets travel around the Sun in *elliptical* orbits with the Sun at one *focus.*

An ellipse is defined mathematically as the collection of points whose combined distance to two fixed points (the *foci*) is equal to a constant. The constant is equal to the length of the long, or *major,* axis of the ellipse (see Box Figure 14-1). This may be easily verified by adding up line segments along the major axis, remembering that the figure is symmetric about both the major and minor (vertical) axes. The degree to which the orbit of a planet (or other rotating object) is elliptical is called its **eccentricity**. For Earth, the distance from the center of the elliptical orbit to either focus is only 1.7% of the distance from the center to the edge of the ellipse along the major axis. In other words, the foci and the center are nearly indistinguishable, and Earth's orbit is very nearly circular. The eccentricity (often designated as e) is expressed numerically as this percentage in decimal form ($e = 0.017$).

Because planetary orbits are eccentric, Earth is closer to the Sun at some times of the year than at others. The point of closest approach is called **perihelion**, and the point of maximum Earth–Sun distance is called **aphelion** (see Box Figure 14-1). The amount of sunlight hitting Earth is slightly greater at perihelion than at aphelion (as we will see in "Critical-Thinking" Problem 2). Perihelion occurs on January 3, 13 days after the Northern Hemisphere winter solstice, so Northern Hemisphere winters are somewhat milder than Southern Hemisphere winters. They are also somewhat shorter, as the planet moves faster at perihelion than at aphelion, according to Kepler's second law. Conversely, Northern Hemisphere summers tend to be longer and milder than Southern Hemisphere summers.

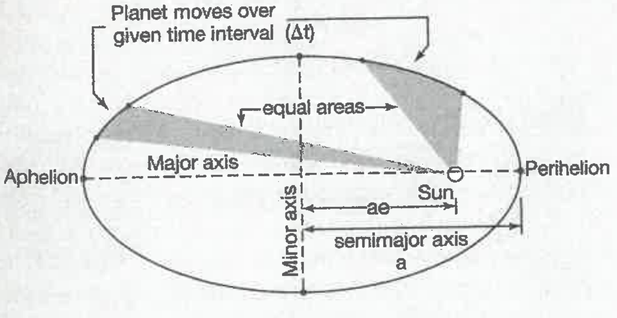
Another factor that affects Earth's climate is the planet's **obliquity**, the fact that its spin axis is tilted 23.5 degrees from the perpendicular to the plane of its orbit. Obliquity creates the contrast between the seasons (Chapter 4); with no obliquity, the annual variation in the amount of solar insolation (resulting from the eccentricity of the orbit) would be very small. Winter and summer would basically not exist. Earth's relatively high obliquity means that there is a large **seasonal temperature contrast** between summer and winter. The eccentricity of Earth's orbit causes this seasonal temperature contrast to be slightly greater in the Southern Hemisphere than in the Northern Hemisphere.

THINKING QUANTITATIVELY

Kepler's Laws

First law: The orbit of each planet is an ellipse with the Sun at one focus.

Half of the major axis of an ellipse is called the *semimajor axis*. This is also the average planet–Sun distance. The semimajor axis is usually represented by the letter a. The distance from the center of the ellipse to one focus is equal to the length of the semimajor axis (a) multiplied by the eccentricity (e) (see Box Figure 14-1). In other words, the eccentricity of the ellipse can be determined by dividing ae by a. An ellipse with zero eccentricity is a circle (the two foci coincide with the center of the circle). Earth's current eccentricity is 0.017; Earth's orbit is nearly circular, but not quite.



BOX FIGURE 14-1 Earth's elliptical orbit, showing the Sun at one focus. (*Source:* From T. McKnight, *Physical Geography: A Landscape Appreciation,* 6/e, 1999. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Second law: A line joining a planet to the Sun sweeps out equal areas in equal times.

Box Figure 14-1 shows that to sweep out an equal area (each shaded region) in the same amount of time (Δt), Earth must travel farther around the perimeter of the ellipse when it is close to the Sun than when it is far from it. From a practical standpoint, then, this law means that the planet moves faster when it is closer to the Sun and slower when it is farther away.

Third law: The square of a planet's orbital period is proportional to the cube of its semimajor axis.

A planet's orbital *period* is the time that it takes the planet to go around the Sun. If we express the period P in Earth years and the planet's semimajor axis a in astronomical units (AU, the average Earth–Sun distance), we can replace the word *proportional* with *equal* and write Kepler's third law as: $P^2 = a^3$.

Changes in Earth's Orbit through Time

Milankovitch's theory predicts that the gravitational influences of the Moon and the other planets, combined with Earth's slightly nonspherical shape, induce small but important variations in Earth's orbital parameters. These variations affect the amount of summertime insolation at high northern latitudes, triggering the onset and end of glacial intervals.

Precession of the Spin Axis

The most noticeable change in Earth's orbit has to do with the direction of its spin axis. The spin axis moves around in space because of the pull of the Sun and the Moon on Earth's equatorial bulge. (See the Box "Thinking Quantitatively: Effect of the Sun and Moon on Earth's Obliquity and Precession.") Currently, the spin axis is oriented such that the North Pole points almost directly at the bright star *Polaris,* otherwise known as the North Star. The direction of the spin axis remains constant as Earth orbits around the Sun, so the North Star remains at geographic north during both summer and winter.

The spin axis has not always pointed in that direction, however. Egyptian pyramids built in 3000 B.C. were designed to observe the north star of the time, *Alpha Draconis,* not *Polaris.* Thirteen thousand years ago, the bright star *Vega* was approximately at geographic north. Over time, the North Pole describes a circle in space as the spin axis points to different parts of the sky. The period of **precession** (i.e., the time it takes for the spin axis to *precess* one complete circle) is 25,700 years. However, the direction of the major axis of Earth's elliptical orbit is also precessing, but in the opposite direction, a phenomenon referred to as the *precession of perihelion.* Because perihelion is precessing in the opposite direction from the spin axis precession, the amount of time required to go through a complete precessional Milankovitch cycle is shorter than 25,700 years. The orbital precession is affected most strongly by two other planets, Venus (because it is close) and Jupiter (because it is big). Thus, two main periods result, at 23,000 and 19,000 years.

Precession modifies the relationship between the seasons and the distance from the Sun shown in Box Figure 14-1. Every half precession cycle, the hemisphere with the greatest degree of seasonal contrast switches between the north and the south. When the Southern Hemisphere has mild summers and winters, the Northern Hemisphere has hot summers and cold winters, and vice versa. Northern Hemisphere glaciation is promoted by a precessional state, as today, with northern summer at aphelion and thus low seasonal contrast. The maximum interglacial condition was achieved 9,000 years ago, with hot summers in the north.

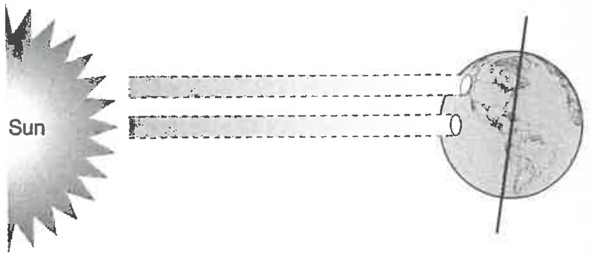
Obliquity Variations

The same phenomenon that causes Earth's spin axis to precess also causes the obliquity to vary from 22 to 24.5 degrees, with a dominant cycle length of about 41,000 years. If you observe a spinning top carefully, you will notice that it, too, undergoes periodic changes in its tilt as its spin axis precesses. This effect becomes more pronounced as the spin rate of the top decreases: The top begins to wobble. Like precession of the spin axis, a change in obliquity does not alter the total amount of sunlight striking Earth. Rather, it determines the extent of seasonal contrasts: The warmth of summers and the coldness of winters is increased by higher obliquities (Figure 14-6). (See also the Box "Thinking Quantitatively: Effect of the Sun and Moon on Earth's Obliquity and Precession.")

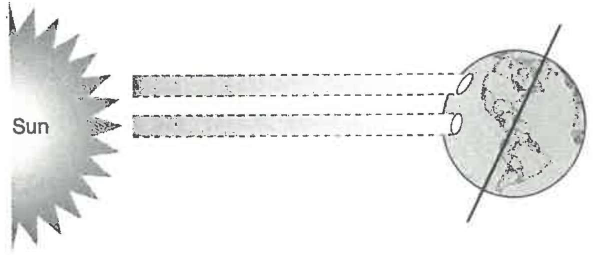
Eccentricity Variations

Earth's eccentricity also undergoes oscillations that can affect climate. The combined gravitational effect of all the planets causes Earth's eccentricity to vary periodically between 0 and 0.06. (Recall that the current value is 0.017.) As was true of the precessional cycle, two main periods are predicted. They are much longer in this case, however: about 100,000 years and about 400,000 years.

The eccentricity variations differ from the precessional and obliquity variations in one other significant respect: Eccentricity variations cause changes in the annually averaged amount of sunlight hitting Earth, whereas precessional and obliquity variations do not. (The direction and steepness of tilt of a planet's spin axis have no direct effect on the total amount of sunlight the planet receives.) One can show mathematically that Earth receives about 0.2% more sunlight at maximum eccentricity than at minimum eccentricity. This difference is thought to be too small to cause major climate shifts by itself, but it might have some effect if it is amplified by a feedback mechanism (discussed later in this chapter).



(a) Low obliquity



(b) High obliquity

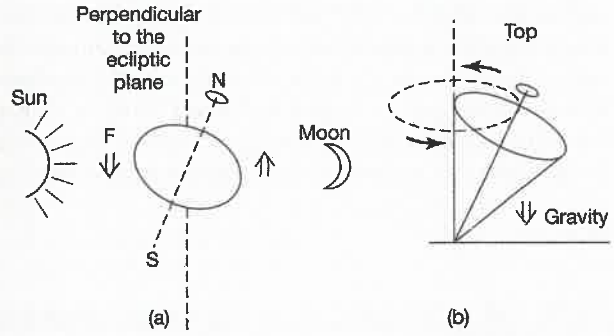
FIGURE 14-6 (a) At low obliquity, Earth has less contrast in insolation between the seasons. (b) At high obliquity, the seasonal contrast is greater.

THINKING QUANTITATIVELY

Effect of the Sun and Moon on Earth's Obliquity and Precession

The fundamental reason why Earth's spin axis precesses, and one reason why its obliquity varies, is because Earth is not perfectly round. Because it is spinning rapidly, it bulges slightly at the equator. The diameter through the equator is 12,756 km, while the polar diameter is about 43 km less. The Sun and the Moon pull on this bulge gravitationally (Box Figure 14-2a), thereby causing Earth's spin axis to precess in a circle and also to bob up and down slightly, giving rise to periodic variations in Earth's obliquity.

The same phenomena can be observed in a simple home experiment with a spinning top (Box Figure 14-2b). Earth's gravity is pulling the top toward the floor. If the top is standing straight up, the gravitational pull is along the top's spin axis, and the top spins smoothly, without precessing. If the top is tilted sideways, however, then the gravitational pull is partly perpendicular to the spin axis, and the top precesses around in a circle. As its rotation rate slows down (due to friction with the surface), the top will also begin to bob up and down, or *nutate*. This nutation is analogous to changes in Earth's obliquity.



BOX FIGURE 14-2 The effects of the Sun and Moon on Earth's obliquity. (a) Both the Sun and Moon exert a torque on Earth, causing it to precess and bob up and down. (b) Analogous motion of a top spinning on its side.

What would happen to this system if one took away the Moon? (This is not just a hypothetical question; there may be Earthlike planets around other stars that lack large moons.) The Moon accounts for roughly two-thirds of the gravitational force acting on Earth's equatorial bulge. The Sun accounts for the other one-third. If the Moon were not present, the net force would be smaller, and Earth's spin axis would precess more slowly. Jacques Laskar and his colleagues at the University of Paris have shown that under these circumstances, Earth's obliquity would vary chaotically from 0° to as much as 60° on a time scale of tens of millions of years. (The reason is that the period of the spin axis precession would now match up with periods observed in the orbits of the other planets, such as the precession of their perihelia.) This would wreak havoc with Earth's climate. Continents located at high latitudes, like much of North America and Europe, would be subject to extreme seasonal variations. This has led some astronomers to suggest that a large moon may be necessary in order for a planet to have a stable obliquity and climate. In reality, the situation is more complicated than this because a more rapidly spinning Earth would *not* experience this problem, but it is still true that the Moon exerts a major influence on Earth's climate.

Probably more important is the fact that eccentricity influences the climatic effect of the precession cycle. When Earth's eccentricity is nearly zero, there is no difference between the perihelion distance and the aphelion distance from the Sun, so it does not matter when summer or winter occurs. When the eccentricity is large, Northern Hemisphere glaciation is especially favored when precession causes Northern Hemisphere summer to occur at aphelion. Of course, within a half precession cycle the situation reverses, with Northern Hemisphere summer at perihelion. Nevertheless, analysis of past glaciations indicates that ice sheets survive this effect of high eccentricity. At present we are at low eccentricity, and according to the calculations of Belgian astrophysicist André Berger, the eccentricity will be decreasing to a minimum near zero in about 30,000 years from now. With eccentricity so low, the unusually cold winters needed to initiate Northern Hemisphere ice-sheet growth don't occur. Thus, climatologists predict that the present interglacial will be long-lived (at least 1.5–2.5 precession cycles). The buildup of carbon dioxide in the atmosphere from fossil-fuel burning only serves to strengthen that prediction.

Comparing Orbital Forcing and Climatic Response by Means of Oxygen Isotopes

The combination of these various orbital forcings causes Earth's climate system to oscillate between two states. The situation can be displayed in a diagram similar to that developed for Daisyworld (Chapter 2). The glacial and interglacial states are represented as valleys separated by a ridge (Figure 14-7). Presumably the glacial state is situated in a deeper valley than the interglacial state, because a greater fraction of Pleistocene time was spent in glaciation. Orbital forcings continually rock the system back and forth. Since 700,000 years ago, the amplitude of this rocking has exhibited a strong 100,000-year periodicity. When these variations exceed a threshold, the system moves over the ridge into the other state. High eccentricity increases the amplitude of the variations on precessional

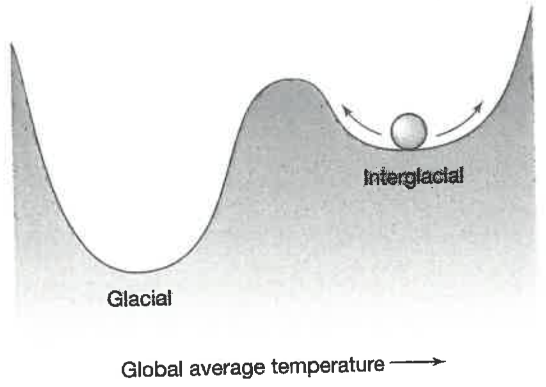


FIGURE 14-7 Stability of the glacial and interglacial states, relative to the changes in high-latitude Northern Hemisphere insolation that rock the state of the system back and forth.

cycles and thus is more likely to be associated with transitions from interglacial to glacial states (or vice versa).

We can now piece together the various parts of the astronomical theory of the Ice Ages described previously and test the theory against the oxygen isotopic record of temperature and sea-level changes during the Pleistocene. The precession, obliquity, and eccentricity variations can all be described mathematically, and the resulting equations can be solved for the amount of insolation received on a monthly or annual basis for any particular latitude. This is nothing new, of course; Milankovitch made these calculations many decades ago. However, some improvements have been made on the original calculations by Milankovitch. The particular result shown at the top of Figure 14-8 is the average monthly insolation (Q) for June, at 65° N latitude.

Shown at the bottom of Figure 14-8 is the past 400,000 years of the oxygen isotope record from Figure 14-4. Is the observed climate response ($\delta^{18}O$) the expected response to the climate forcing (Q)? Such a comparison is difficult; indeed, we might conclude from a visual inspection that the two curves are unrelated. However, the wiggles of these curves can be considered as the combination of a number of waves of different frequency (the mathematical inverse of period) and amplitudes, much as a musical chord is the combination of a number of notes, each of a different frequency (pitch). These curves can then be separated into their component periodic waves (or *bands*); the most important ones are shown in Figure 14-8. (The technical name for this procedure is *Fourier analysis*.) For Q these are the precession, obliquity, and eccentricity bands. As predicted by Milankovitch's astronomical theory, the

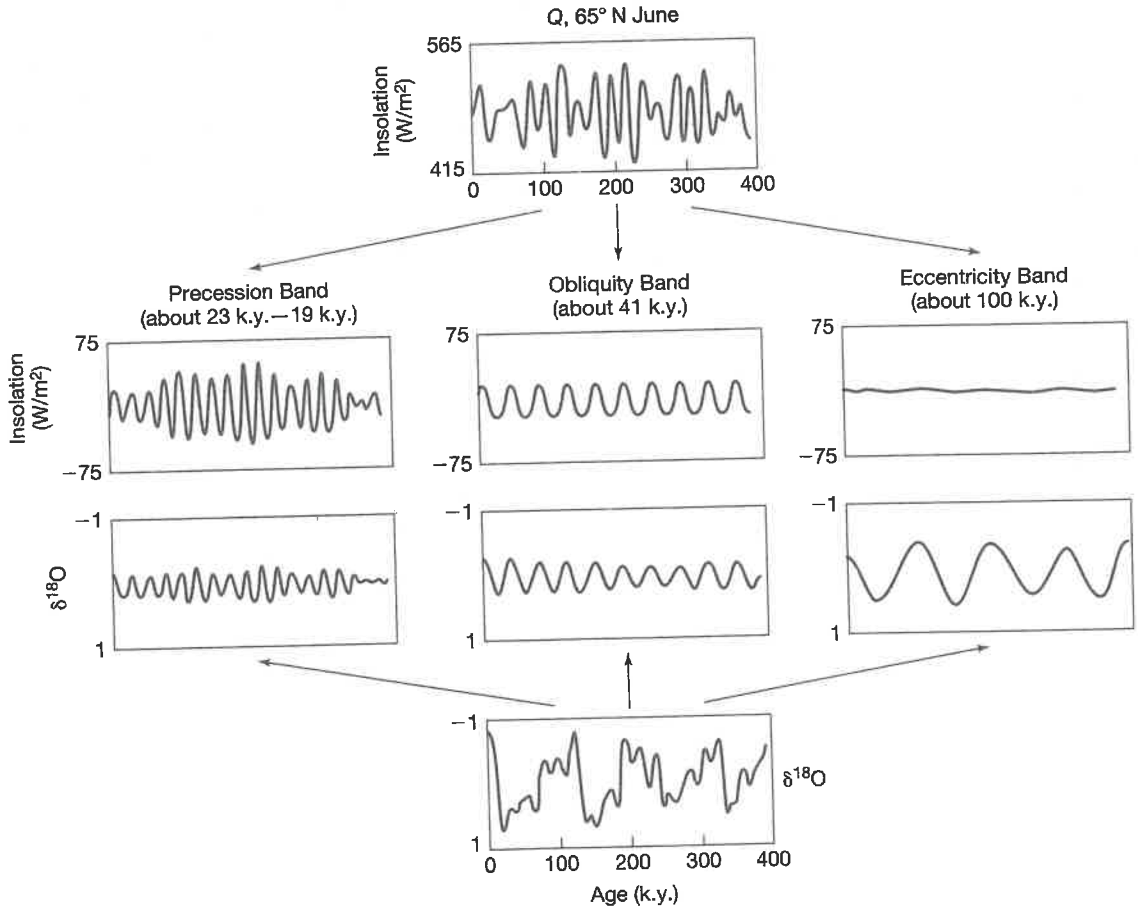


FIGURE 14-8 Northern Hemisphere June insolation (Q, the climate forcing) and marine oxygen isotopic composition ($\delta^{18}O$, the climate response) and their dominant periodic components. (*Source:* Imbrie et al., *Paleoceanography* 7, 1992, pp. 701–738.)

dominant periodicities of the $\delta^{18}O$ record occur at these same bands (19,000 years and 23,000 years, 41,000 years, and 100,000 years, respectively). Thus, there is compelling evidence that the pacemaker for the ice ages is the "Milankovitch" signal.

Moreover, the amplitude of the response to the precession and obliquity changes seems to be roughly proportional to the amplitude of the forcing. These observations suggest that a simple link exists between fluctuations in the amount of radiation received at high latitudes and the extent of glaciation.

A closer inspection of Figure 14-8, however, reveals an important departure from a straightforward link between climate forcing and climate response: The direct forcing, that is, the average annual insolation change, in the eccentricity band is very small (some 10% of that in the other bands), yet the climate response is the largest of the three bands. The importance of eccentricity is evidently more indirect. Eccentricity modulates the insolation changes associated with the precessional band, as can be seen in the envelope of variation for precession in Figure 14-8. Nevertheless, climate amplification of the 100,000-year forcing is considered necessary to create the climatic response from eccentricity forcing. Do positive feedback loops in the climate system amplify the weak eccentricity forcing into the major climatic response to orbital fluctuations?

GLACIAL CLIMATE FEEDBACKS

The timekeepers for the glacial–interglacial climate fluctuations during the Pleistocene were subtle, periodic changes in Earth's orbital parameters. However, these changes have been small. Moreover, the dominant periodicity of glacial–interglacial fluctuations has been 100,000 years; if this phenomenon is the result of eccentricity changes, an amplifier is needed. The important climate variables that we need to consider are albedo and the greenhouse effect. Clearly, the growth of continental ice sheets influences the albedo of the planet, so this effect must be incorporated into any model that attempts to explain Pleistocene climates. Clouds exert a major control on planetary albedo, and we may wonder whether the cloud albedo varies in concert with the Milankovitch cycles. Finally, we have seen how changes in the greenhouse effect of atmospheric CO_2 have affected climate on long time scales; perhaps the Pleistocene climate system has responded to more rapid fluctuations in atmospheric CO_2.

Ice–Albedo Feedbacks

Any change in the seasonal distribution of solar luminosity that affects the growth of ice during the winter or the meltback during the summer has the potential to affect the planetary albedo (see Chapter 3). As ice sheets begin to grow, they convert a region that previously had reduced albedo during the summer, as snow melted, to one that maintains high albedo throughout the year. The average annual albedo thus increases, which will lead to both a regional and a global cooling. This cooling will accelerate the growth of the continental ice and will allow it to spread to lower latitudes.

The positive ice–albedo feedback, involving global temperature, ice-sheet growth, and albedo (Figure 14-9), was introduced in Chapter 3. In Figure 14-9 the forcing is also indicated; note that a small change in the intensity of summer insolation at high northern latitudes could potentially lead to large changes in ice-sheet coverage and global temperature. Researchers have shown that the growth and destruction of the Northern Hemisphere ice sheet has a characteristic response time of about 100,000 years. Thus, the dynamics of glaciation are especially tuned to a frequency of one cycle per 100,000 years and should respond quite sensitively to eccentricity-induced changes. Numerical models show that instabilities develop as an ice sheet becomes very large, such that fairly subtle changes in high-latitude insolation can lead to its catastrophic destruction.

The ice–albedo feedback has significant effects on Northern Hemisphere climates, but can't explain why Southern Hemisphere climate changes are both large and in step with those in the Northern Hemisphere. Studies of polar ice cores indicate that carbon dioxide levels have also varied substantially. The greenhouse effect associated with these changes is not negligible, and may be the explanation for the link between northern and southern climate change. Ice cores also reveal that the number of cloud condensation nuclei in the atmosphere has changed with the Milankovitch cyclicity. We now explore some of the proposed mechanisms for large and rapid changes in atmospheric CO_2 levels and cloud condensation nuclei on glacial time scales.

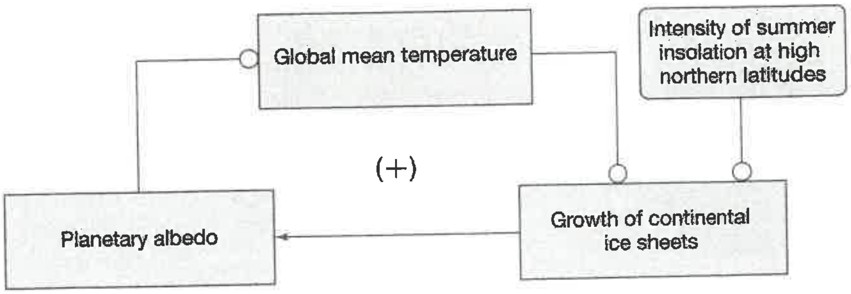


FIGURE 14-9 Feedback diagram showing the effect of changes in glacial growth on global temperature.

Evidence from the Vostok (and Dome C) Ice Cores

During the Southern Hemisphere summer of 1982–1983, French and Soviet scientists met in Vostok, on the high plateau of Antarctica, to take samples from the longest, most continuous ice core ever recovered from the Antarctic Ice Sheet. With each length of ice removed from this 2-km-deep hole, our knowledge of Earth's climate history was extended millennia into the past. By the time the last, deepest section was recovered and sampled, 200,000 years of ice accumulation were revealed. The samples were taken to France, where the oxygen isotopic composition of the ice was analyzed. This analysis revealed a history that matched well what we would expect from the marine record of isotopic changes during the Pleistocene. Since then, the coring has been extended to 3.3-km depth at a nearby site, Dome C (see Chapter 1), revealing ice deposited some 800,000 years ago.

However, one of the most important discoveries made by the scientists studying the Vostok ice core was the realization that the ice contained air bubbles frozen into the glacier as it grew. Using extreme care, the scientists were able to measure the concentration of carbon dioxide in the bubbles. We saw the results of this effort in Chapter 1, and we also learned that air bubbles in ice cores have also been used to estimate atmospheric CO_2 concentrations on much shorter time scales (the past 1,000 years). The Vostok core gives us long time scales because the rate of snow accumulation at Vostok is very small, a few centimeters per year. By contrast, snowfall at Siple Station, where the data from Chapter 1 were collected, is many meters per year.

The results of the Vostok scientists' analyses provide a firm link between global climate change and variations in the quantity of greenhouse gases in the atmosphere. What they found is that the CO_2 concentration falls and rises in concert with variations in local temperatures (recorded in the hydrogen isotopic composition of the ice; see Figure 1-9), and both records are well correlated with global changes in temperature and ice-sheet size determined from $\delta^{18}O$ variations.

The rapidity of some of the changes is truly remarkable. The increase from glacial-stage levels (about 190 ppm) to nearly contemporary CO_2 levels (240 ppm) occurred over only 4,000 years, between 16,000 years and 12,000 years ago. Analyses of bubbles from ice created during the next-to-last deglaciation, approximately 145,000 years ago, display a similarly rapid rise in CO_2. The drop in CO_2 levels from the previous interglacial (about 130,000 years ago) to the height of the last glacial (about 20,000 years ago) was more subdued—about 1 ppm per millennium. The sawtooth nature of these changes is nearly identical to the oxygen isotope record, suggesting a close link between CO_2 changes, ice volume, and global temperature.

Feedbacks Affecting Atmospheric CO_2 on Glacial Time Scales

In Chapters 8 and 12 we found that on long time scales (millions of years) the carbonate–silicate geochemical cycle, together with the weathering and deposition of organic carbon-rich sedimentary rocks, determines the steady-state atmospheric CO_2 level. When studying glacial–interglacial fluctuations, however, other processes must be included because the assumption of steady state with respect to these processes may not be valid on shorter time scales (thousands to hundreds of thousands of years). The partitioning of carbon between the atmosphere and terrestrial biomass, and between the atmosphere and ocean, as affected by the oceanic biological pump (Chapter 8), are potentially of great importance to the CO_2 balance during glacial cycles. So, too, are the processes of limestone weathering and limestone deposition. On glacial–interglacial time scales, limestone weathering need not be balanced by limestone deposition, and any imbalance will affect atmospheric and oceanic concentrations of CO_2. Let us explore these feedbacks in greater detail.

ROLE OF THE BIOLOGICAL PUMP The photosynthetic conversion of dissolved carbon dioxide to organic matter in the surface ocean, the settling of this material through the water column, and its decomposition at depth (that is, the *biological pump,* described in Chapter 8) dominates the distribution of carbon throughout the world's ocean. Because the atmosphere equilibrates with the surface ocean, that photosynthetic conversion dominates the atmospheric CO_2 content as well. An atmospheric CO_2 pressure of 280 ppm (the preindustrial level) represents a biological pump that operates at intermediate efficiency, because regions of the ocean exist today (and presumably in preindustrial times as well) where nutrient concentrations are not completely depleted by biological uptake (Chapter 8). If nutrients were completely utilized—that is, if the biological pump were 100% efficient in removing nutrients and CO_2 from surface waters—the atmospheric CO_2 pressure would be reduced to about 165 ppm. At the other extreme, if the biological pump ceased completely, the atmospheric CO_2 level would rise to about 720 ppm as the CO_2-charged deep waters mixed with the surface waters and homogenized the chemical composition of the ocean. Thus, the low CO_2 concentrations of glacial intervals might be the result of a more efficient biological pump.

Why might the glacial ocean support greater biological productivity? Most of the answers proposed in the scientific literature involve increased nutrient supply through upwelling or riverine delivery. The hypotheses described next are intended to explain why nutrients might have been more available to the oceanic biota during glacial times.

SHELF NUTRIENT HYPOTHESIS The CO_2 concentration at the height of the last glaciation (20,000 years ago) was about 190 ppm. Might the biological pump have been more effective during the glaciation than it is today, perhaps as a

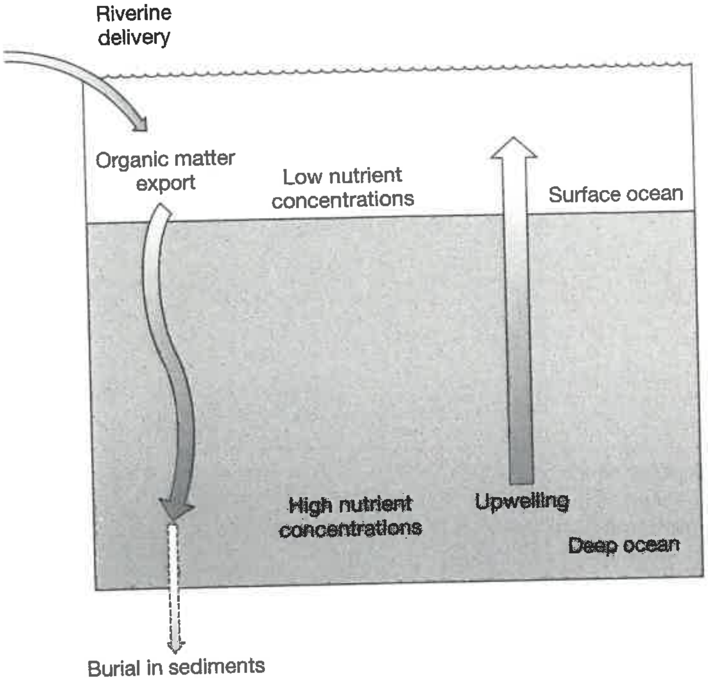


FIGURE 14-10 Simplified view of the nutrient throughput of the oceans.

result of a higher concentration of nutrients in the ocean as a whole? The nutrient concentration of the ocean represents a balance between supply by rivers (and, for nitrogen, by bacterial processes that convert nitrogen gas from the atmosphere to nutrient nitrate) and removal, primarily by sedimentation of organic matter (Figure 14-10). Thus, if the biological pump was intensified by higher nutrient concentrations during glacial intervals, either riverine fluxes were greater or sedimentation rates were lower.

As the glaciers grew, sea level fell, exposing the vast, low-relief margins of the continents (the **continental shelves**). Sediments of the continental shelves are rich in organic matter and nutrients, as the result of the highly productive nature of the overlying waters. When these sediments became exposed, weathering reactions released the nutrients (especially phosphate) to the rivers draining the shelves (Figure 14-11). This nutrient release enhanced the global delivery of phosphate to the oceans, causing an increase in oceanic phosphate concentrations, marine productivity, and carbon export from the surface ocean and a drop in atmospheric CO_2. The resulting effect on global temperature and ice volume created a positive feedback loop, as shown in Figure 14-12. An attractive aspect of this hypothesis is that the residence (response) time of phosphate in the ocean is about 40,000 to 100,000 years, which essentially matches the major periodicity of glacial–interglacial cycles. The oceanic phosphate cycle is thus "tuned" to a major Milankovitch frequency and should be able to provide at least part of the required amplification of the Milankovitch forcing.

However, there are problems with this *shelf nutrient hypothesis*. The distribution of the trace element cadmium throughout the ocean follows that of phosphate very closely. Cadmium is incorporated into $CaCO_3$ skeletons of bottom-dwelling organisms in proportion to its oceanic concentration, whereas phosphate is not. Thus, paleoceanographers

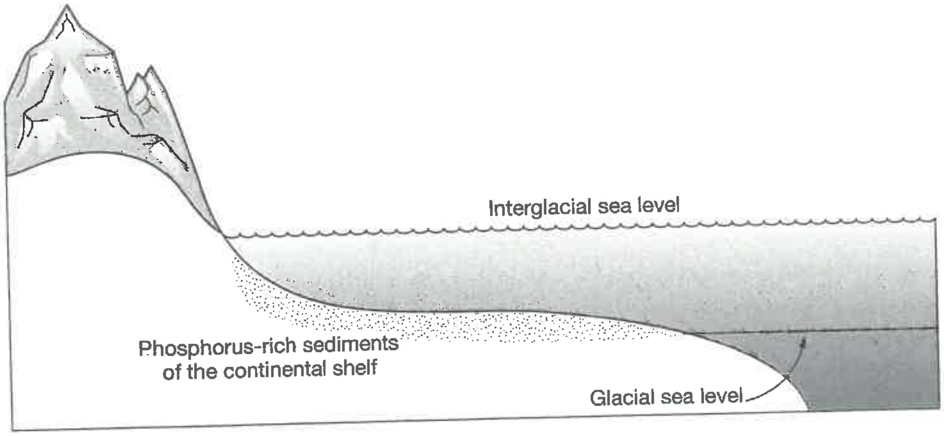


FIGURE 14-11 The exposure of nutrient-rich shelf sediments as a result of a drop in sea level, part of the shelf nutrient hypothesis for the cause of changes in biological productivity on glacial time scales.

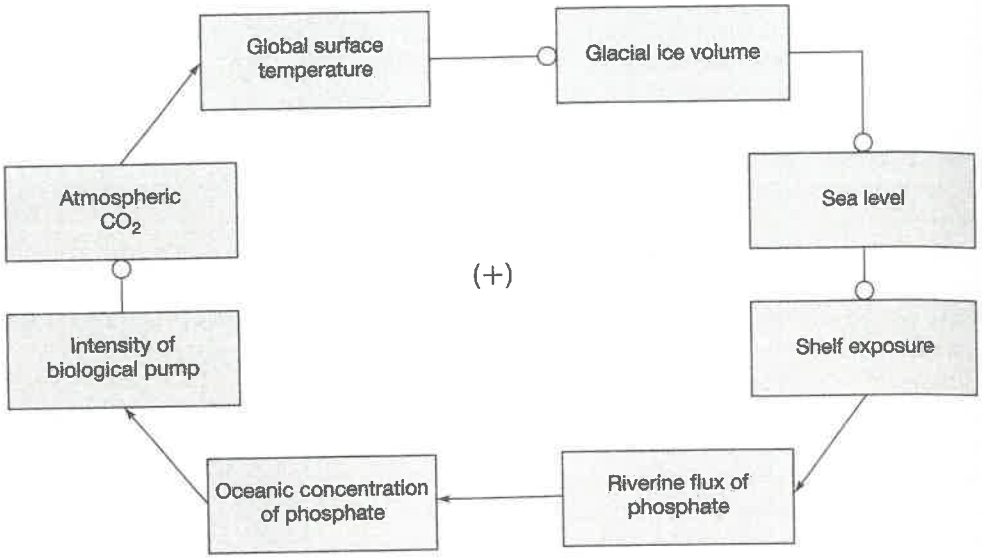


FIGURE 14-12 Systems diagram of the shelf nutrient hypothesis for the reduction of atmospheric CO_2 during glaciation.

use the cadmium content of the fossils of bottom-dwelling foraminifera as a proxy indicator of changes in the phosphate content of the oceans in the past. What these researchers find is that the cadmium content of these fossils does not indicate higher phosphate concentrations during glacial intervals. This inconsistency has led scientists to shift the focus of their search for productivity changes to other nutrients, particularly iron.

THE IRON FERTILIZATION HYPOTHESIS Iron plays an important role in limiting primary productivity in certain regions of the ocean (Figure 14-13). In these regions the major nutrients are not depleted as they are in the rest of the surface ocean (Chapter 8), and productivity appears to be limited by trace nutrients such as iron. Moreover, nitrogen-fixing cyanobacteria have large demands for iron, which is an essential metal for the synthesis of the enzyme that catalyzes nitrogen fixation (see Chapter 11). Much of the iron supplied to the oceans today comes from windblown dust particles, which typically have a coating of iron that dissolves in seawater. The Saharan and Gobi deserts today provide considerable quantitities of dust to the Atlantic and Pacific oceans, respectively.. Aridity appears to have increased during glacial times. Furthermore, the east–west winds should have intensified in response to the greater equator-to-pole temperature gradient (Chapter 4). Both of these factors would have increased the flux of dust to the oceans during glacial times. The record of windblown dust accumulation in marine sediments supports this *iron fertilization hypothesis;* rates increase severalfold during glacial intervals.

Recognition that primary productivity in large regions of the world's oceans is iron-limited today has led to the suggestion that fossil-fuel emission of carbon dioxide might be countered by iron-induced stimulation of biological uptake of CO_2 and its transfer to the deep sea (via the biological pump; see Chapter 8). Small-scale ocean experiments have indicated that iron fertilization is feasible, but also reveals that there may be detrimental and unexpected consequences of this environmental manipulation, including depletion of dissolved oxygen in the deep ocean.

THE CORAL REEF HYPOTHESIS The continental shelves between 30° N and 30° S latitude provide a habitat that is ideal for the growth of corals and other calcium carbonate-secreting organisms (Figure 14-14). As these organisms

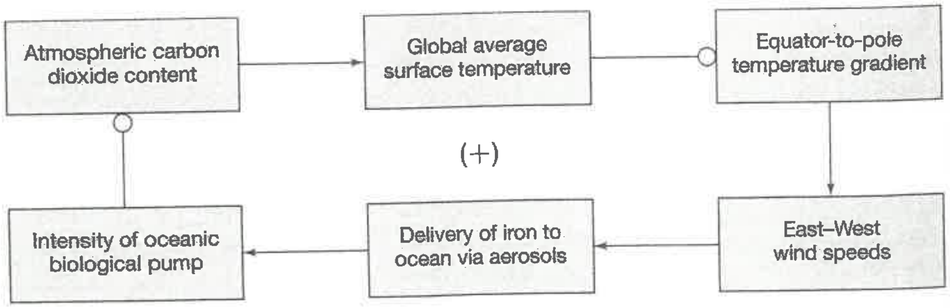


FIGURE 14-13 The iron fertilization hypothesis for the intensification of the biological pump during glaciations.

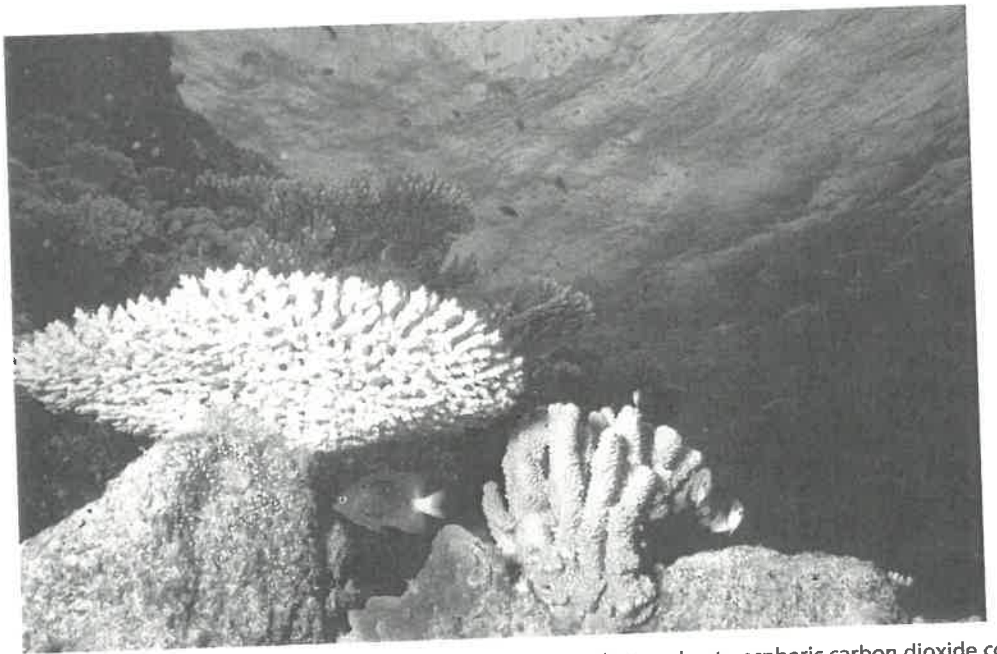


FIGURE 14-14 [See color section] Coral reefs may be responsible for the changes in atmospheric carbon dioxide concentrations that occur between glacials and interglacials. (*Source:* Photos.com/Jupiter Images Unlimited.)

grow, they add incrementally to the rock framework of the reef, building laterally as well as vertically, until the water surface is reached.

As we saw in Chapter 8, the production of $CaCO_3$ can be written as follows:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O.$$

Thus, the growth of coral reefs serves as an additional source of carbon dioxide to the atmosphere. (The effect is only temporary, however; after tens of thousands of years, this excess carbon dioxide becomes converted to bicarbonate, as the result of mineral weathering, and is redeposited as $CaCO_3$.) In contrast, when ancient reefs are exposed by a drop in sea level, chemical weathering leads to their dissolution. This process is the reverse of reef growth: Atmospheric CO_2 is converted into bicarbonate, which is carried by rivers to the ocean. Thus, the growth and destruction of coral reefs can affect atmospheric CO_2 on glacial–interglacial time scales.

The link to glacial–interglacial CO_2 fluctuations is once again through sea-level changes. As the glacial interval ends and the ice sheets begin to melt, sea level rises, flooding the continental shelves. In the tropics, reef growth resumes and CO_2 is released to the atmosphere. The increase in atmospheric CO_2 causes an increased greenhouse effect, thereby amplifying the original climate warming (Figure 14-15). Conversely, as sea level begins to fall at the end of the interglacial, reefs become exposed to the atmosphere, and rain, soil, and groundwaters begin the process of reef dissolution. Again, the feedback loop is positive.

The importance of this feedback depends on the rates of these processes and on how responsive the rates are to sea-level changes. Studies of rates of calcium carbonate formation by reef-building organisms indicate that the reef ecosystem can easily keep pace with sea-level rise. The rate of limestone dissolution, however, is relatively slow. Thus, it is possible that, in this *coral reef hypothesis,* there is an unbalanced response to sea-level rise and fall in terms of reef growth and dissolution.

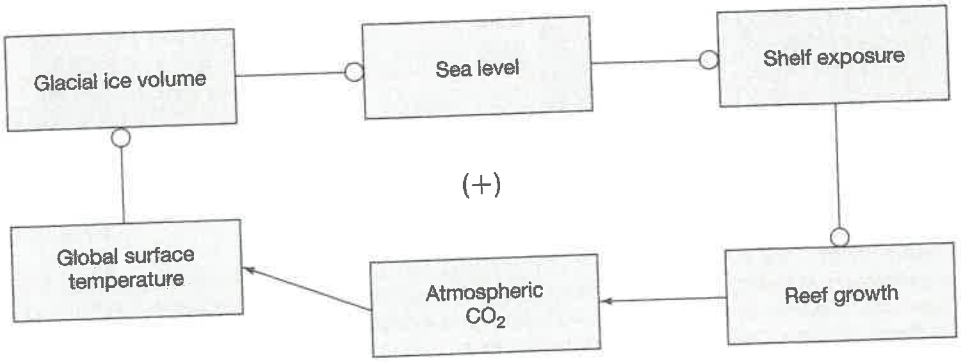
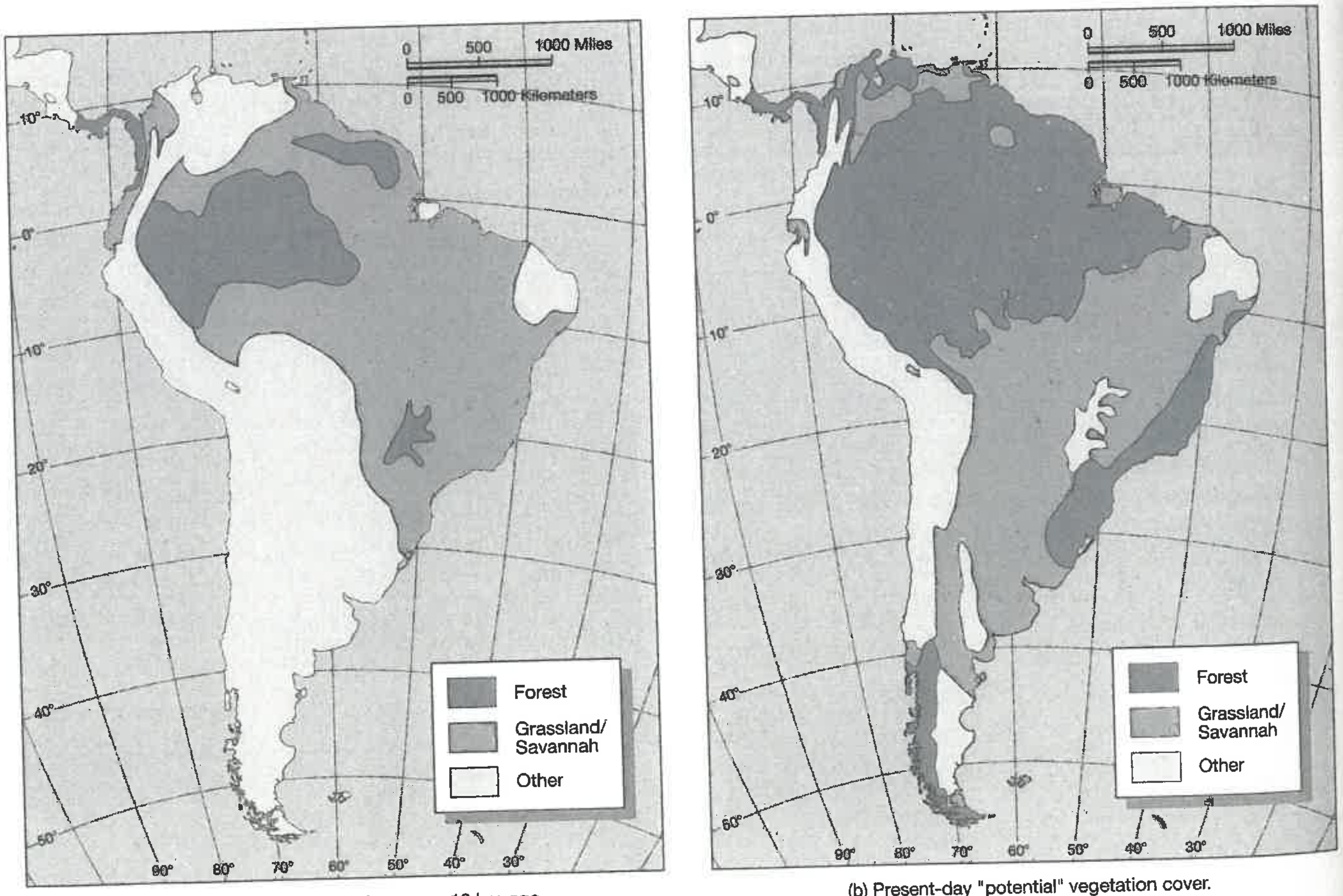


FIGURE 14-15 Systems diagram of the coral reef hypothesis.

Coral reefs are suffering from a host of diseases and other influences today. These are probably the result of multiple stresses, including warmer sea temperatures, increased human perturbation (ship groundings, pollution, destructive collection of reef rock and reef organisms), and perhaps even an increase in the flux of dust from distant lands carrying pathogens and iron, which fertilizes the algal competitors of corals. Perhaps the most pervasive anthropogenic stress is the direct response of the ocean's carbon chemistry to increasing atmospheric CO_2. Recall that as atmospheric CO_2 increases, the pH of the surface ocean decreases and the carbonate ion concentration falls. Carbonate, together with calcium ion, is essential for corals to precipitate their skeletons. The historical rise of atmospheric CO_2 over the last century has reduced the carbonate ion concentration of ocean surface waters by a measurable amount and may already be causing significant stress to corals. Projections for the future are not encouraging: corals may lose their ability to precipitate skeletons by early in the next (22nd) century. Scuba divers, or rather those who hope that their descendants will enjoy scuba diving, along with those who recognize the intrinsic and societal value of coral reefs thus have an additional reason to be concerned about future CO_2 increases.

Changes in Terrestrial Biomass: A Negative Feedback

In living tissue, the terrestrial biomass today contains about the same amount of carbon (600 Gton[C]) as does the atmosphere; about twice that much is contained in dead and decaying organic material in soils. On the basis of studies of plant fossils and other climatic indicators, it appears that the amount of forest coverage, and thus terrestrial biomass, was drastically reduced during the last glacial interval (Figure 14-16). Much of the northern forests were covered with ice, and tropical regions experienced greater aridity and thus the replacement of tropical rainforests with grasslands. Estimates have been made of the total amount of carbon that was transferred from the oceans to the terrestrial biomass at the end of the last glaciation. These numbers have large uncertainties, but it is clear that the change (around 700 Gton[C]) was many times larger than the net change in the amount of CO_2 in the atmosphere (around 160 Gton[C]).



(a) Reconstructed vegetation cover, 18 k.y. ago

(b) Present-day "potential" vegetation cover.

FIGURE 14-16 The difference in South American vegetation between (a) the last glacial maximum and (b) today. Note the large increase in forest cover at the expense of grassland and savannah. The present-day map shows the "potential" vegetation cover; deforestation and other human activities have reduced the forest cover from its potential coverage shown here. *(Source:* Courtesy J. Adams, Oak Ridge National Laboratory.)

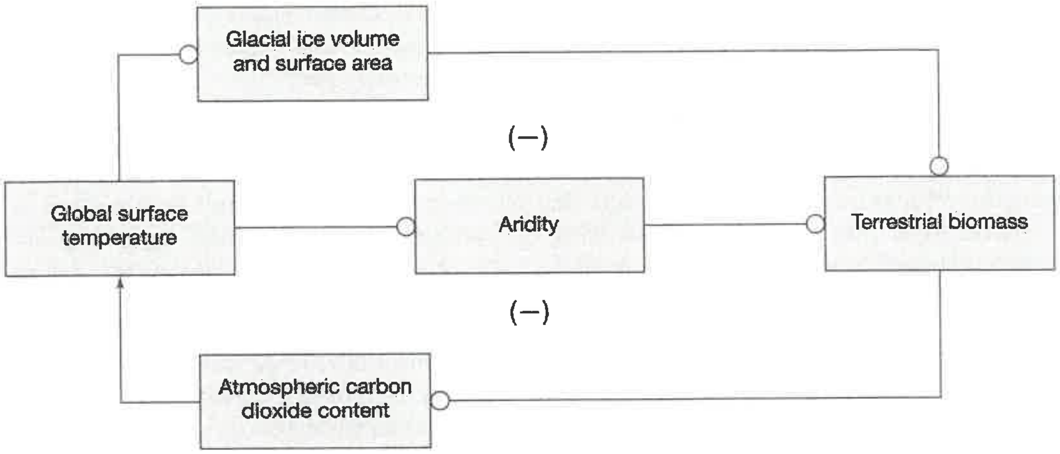


FIGURE 14-17 Systems diagram showing negative feedback between the size of the terrestrial biomass and climate change on glacial–interglacial time scales.

The growth of the terrestrial biomass during deglaciation and its destruction during the initiation of a glacial interval represent the only negative feedbacks that we have been able to identify to changes in atmospheric CO_2 on glacial time scales (Figure 14-17). That the CO_2 level rose and fell in concert with global temperature during the past 220,000 years indicates that positive feedback mechanisms have predominated. Note that this is just the opposite of what would be expected if organisms were modulating the climate system in such a way as to increase ecosystem stability. Gaia, if she exists, is destabilizing on glacial-to-interglacial time scales.

Cloud–Albedo Feedbacks

Recall from Chapter 4 that the process of cloud formation is critically dependent on the presence of small droplets (aerosols) known as *cloud condensation nuclei.* Besides dust (and pollution) over land and tiny sea-salt droplets over the ocean, two compounds are particularly important in the formation of cloud condensation nuclei: **methane sulfonic acid (MSA)** and sulfuric acid. The record of variation in the abundance of these cloud seeds can be read in the sulfur content of glacial ice in Greenland and Antarctica. Analysis of the composition of the Vostok ice revealed that the amount of MSA in the atmosphere of the Southern Hemisphere has varied with temperature over the past 150,000 years (Figure 14-18). During glaciations, the MSA content of the atmosphere over the Southern Ocean apparently was substantially greater than during interglacials. Might this have had a climatic consequence?

Both MSA and sulfur dioxide have an important biological source on the unpolluted Earth. Marine algae produce the gas *dimethyl sulfide* (DMS) as a byproduct

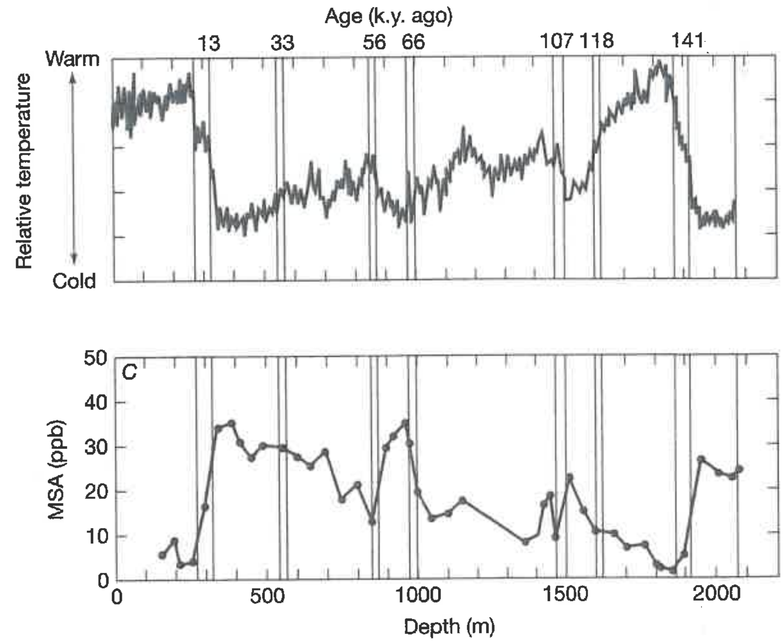


FIGURE 14-18 MSA content of Antarctic ice, compared with the relative local temperature (as indicated by the hydrogen isotopic composition of the ice), over the past 150,000 years. (*Source:* Legrand et al., *Nature* 350, 1991, p. 144.)

of the regulation of the salt content of their cells. DMS escapes to the atmosphere, where it undergoes chemical transformation to either MSA or sulfur dioxide. *Aerosols* (suspended atmospheric particles—in this case, tiny droplets) are formed that can serve as nuclei for the condensation of water vapor in the formation of clouds. It is likely that the rates of production of DMS, MSA, and sulfur dioxide increase as marine algal productivity increases. This increase in aerosol production would increase the aerosol concentration in the atmosphere. As a result, there should be an increase in the number of cloud water droplets in clouds, with a reduction in their size. In turn, cloud albedo would increase and thereby reduce Earth's average surface temperature.

The high content of MSA in ice formed during glacial intervals suggests that the productivity of the glacial ocean was greater than that of the interglacial ocean. Why? Should not marine algae be more productive when water temperatures are warmer? In Chapter 8 we saw that some of the most productive waters of the world are at high latitudes. The detrimental effects of the lack of sunlight and of cold water temperatures on marine algae seem to be more than compensated for in these regions by a high supply of nutrients. Today, a strong thermocline at low latitudes stabilizes the water column and tends to prevent upwelling. In contrast, high-latitude surface waters lack a thermocline. Wind mixing penetrates to great depths and mixes nutrient-enriched deeper waters to the surface. Thus, cooling of higher-latitude temperate waters during glacial intervals should have reduced the thermocline, fostered water-column overturn, and brought a greater nutrient supply to surface waters, supporting higher rates of primary production.

If marine algal productivity tended to increase during glaciations, the feedback loop would be positive: This set of processes would tend to amplify the climate systems response to the Milankovitch forcing (Figure 14-19). The fact that the MSA content of Antarctic glacial ice rises as global temperature falls suggests that this feedback loop is important in Earth's climate system during at least the recent geologic past.

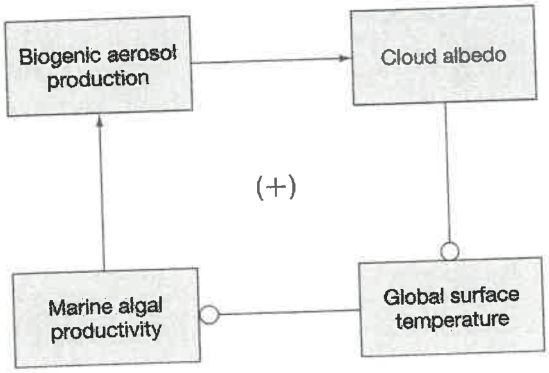


FIGURE 14-19 Cloud–albedo climate feedbacks involving the algal production of cloud condensation nuclei.

The Younger Dryas

In very broad terms, Earth began to warm about 15,000 years ago. The ice sheets that covered large areas of North America and northwest Europe began to retreat. Global sea levels rose as the glaciers melted, and the erosion from large volumes of meltwater reshaped the landscape around the edges of the former ice margins. Vegetation began to colonize the previously glaciated regions, and new vegetation patterns developed as soils formed and temperature and rainfall patterns changed. This spread of milder, more benign conditions came to an abrupt if temporary end 12,900 years ago in a 1,300-year climatic reversal known as the **Younger Dryas** event. The Dryas flower was widespread at that time—giving its name to the climatic event—but is currently found only in arctic and alpine tundra.

Some of the best evidence of climate and vegetation changes during the Younger Dryas comes from pollen and geologic analyses in northern Europe. As the climate warmed after the glacial retreat, there was a general increase in the density of vegetation, particularly grasses and sedges. This increase was followed by an increase in shrubs such as juniper and in willow; in some areas, the shrubs were later replaced by birch woodland. Pollen analysis shows a similar sequence of events in the British Isles, Ireland, and Scandinavia. Geologic evidence indicates that most of Scotland was probably deglaciated by 13,000 years ago. At this point a major climatic reversal occurred. By about 12,300 years ago, there was a new ice sheet several hundred meters thick over western Scotland, and there was renewed advance of valley glaciers in the upland regions of northern Europe. (*Valley glaciers* are individual glaciers that form at the head of a valley in mountainous regions and flow down the valley.) The pollen evidence shows a synchronous change in vegetation. The northern woodland diminished in area and was restricted to a few sites. The vegetation became more open, and the pollen data show a predominance of cold-tolerant vegetation types.

These changes represent a significant climate shift in northern Europe. However, the global impacts of this shift are more subtle. There is evidence of a similar climate shift in New England and along the east coast of Canada. There is little other evidence from North America except in the Gulf of Mexico and the Gulf of California, and there is only limited evidence from the Mediterranean. However, climatic reversals also appear to have occurred in the Andes and in Africa. The strongest evidence from Africa comes from lake levels, which increased after the northern deglaciation. But, while the Younger Dryas event was taking place in northern Europe, much of Eastern Europe and tropical and subtropical

Africa experienced increased aridity. Humid conditions returned to this region at the end of the Younger Dryas, and during the early Holocene, what we know today as the Sahara Desert was primarily grassland (savannah). Furthermore, data obtained from ocean cores taken in the western tropical Pacific Ocean and off the coast of Japan show some indication of a climate change at that time. Glaciers in the Southern Alps of New Zealand also re-advanced during this interval.

The Younger Dryas thus appears to be centered primarily on the North Atlantic region, but nearly synchronous climate changes occurred in many other parts of the Northern Hemisphere, if not globally. What process might explain a shift in climate that has a strong regional, rather than global, focus yet is able to influence widely scattered regions across Earth's surface?

NORTH ATLANTIC DEEP-WATER FORMATION A prime candidate for explaining the strong regional focus of the Younger Dryas climate change is the ocean circulation of the North Atlantic. The relatively high sea-surface temperatures in the northeast North Atlantic, which bring mild conditions to northern Europe today, result from the northward movement of the warm surface waters of the Gulf Stream and North Atlantic Drift. We saw in Chapter 5 that this movement was controlled in part by the atmospheric circulation and in part by the thermohaline circulation. Recall that the North Atlantic thermohaline circulation involves deep-water formation in the Norwegian and Greenland seas: As the cold and highly saline water subsides and moves southward, it is replaced by warm, northward-moving water at the surface. Geochemist Wallace Broecker has suggested that some of the climate changes that accompanied deglaciation resulted from events that cut off or reduced this deep-water formation. One hypothesis is that meltwater from the North American ice sheet, perhaps collected in glacial Lake Agassiz, catastrophically drained eastward through the Gulf of St. Lawrence. The result would have been a large infusion of cold freshwater to the northern North Atlantic. Because freshwater is less dense than saltwater, this infusion would have produced a stable surface layer that would freeze very easily, pushing the sea-ice margin southward and cutting off the formation of the North Atlantic deep water. Both the change in the thermohaline circulation and the southward expansion of the sea ice would have cut off the flow of warm surface water in the North Atlantic Drift, which would have resulted in a significant climate change in the region. Such a process could account for the climate reversal experienced during the Younger Dryas and would also explain the apparent focus on the North Atlantic region.

AN ON–OFF SWITCH IN THE NORTH ATLANTIC Although we have known about the Younger Dryas event for years and we have known that the event took place fairly rapidly (in geological terms), using ice-core data obtained from the Greenland ice cap in the early 1990s, a team led by Richard Alley (a glaciologist at Pennsylvania State University) revealed the startling information that these changes might have taken place in less than a decade. The snow accumulation record (Figure 14-20) shows increased accumulation in the warmer intervals; it also shows that the switch from cold to warm intervals occurred over a very short time span. Atmospheric dust deposited on the ice and recorded in the ice cores reveals similar rapid changes in deposition rates. More dust is deposited during glacials than during interglacials, because the increased north–south temperature gradient results in a stronger atmospheric circulation; that stronger circulation carries more dust. Both the snow accumulation and the dusty deposition, therefore, indicate a shift in the atmospheric circulation. The rapidity with which these changes occur suggests that the system switches almost instantly between two modes of circulation.

The exact mechanism for explaining the shift in circulation is the subject of much speculation and discussion. One suggestion is that attributing the cause to any single process may be a mistake. An alternative approach is to view the system as chaotic. *Chaos theory* represents a rapidly emerging branch of science dealing with dynamic systems. Chaotic systems are iterative: The state of the system at one point in time is dependent on the state at the previous point. However, a characteristic of these systems is that very slight changes in the starting point are amplified through positive feedbacks, so the possible results diverge rapidly after only a short interval. Almost identical starting points can result in very different outcomes, and different starting points can produce outcomes that are very similar. The consequence is that, after a certain interval, the system becomes essentially unpredictable (refer back to "Critical-Thinking" Problem, in Chapter 13).

In 1960, Edward Lorenz, a meteorologist at the Massachusetts Institute of Technology, was the first to recognize that the atmosphere is a chaotic system. Since then we have known why accurate long-range weather forecasting is impossible and why accurate daily weather forecasts can be effective only on time scales of days to a couple of weeks. One important attribute of chaotic systems, however, is that they exist in quasi-equilibrium states; in the case of the atmosphere, for example, we know in general what it will be like next year, even though we cannot predict exactly what it will be like on any given day. In the terminology of chaos theory, these quasi-equilibrium states are called *strange attractors:* The system is never precisely at that point, but it is always somewhere close to it. Another characteristic of chaotic systems is that they may switch rapidly between two or more of these quasi-equilibrium states. The point at which this switch occurs is called a *bifurcation point.*

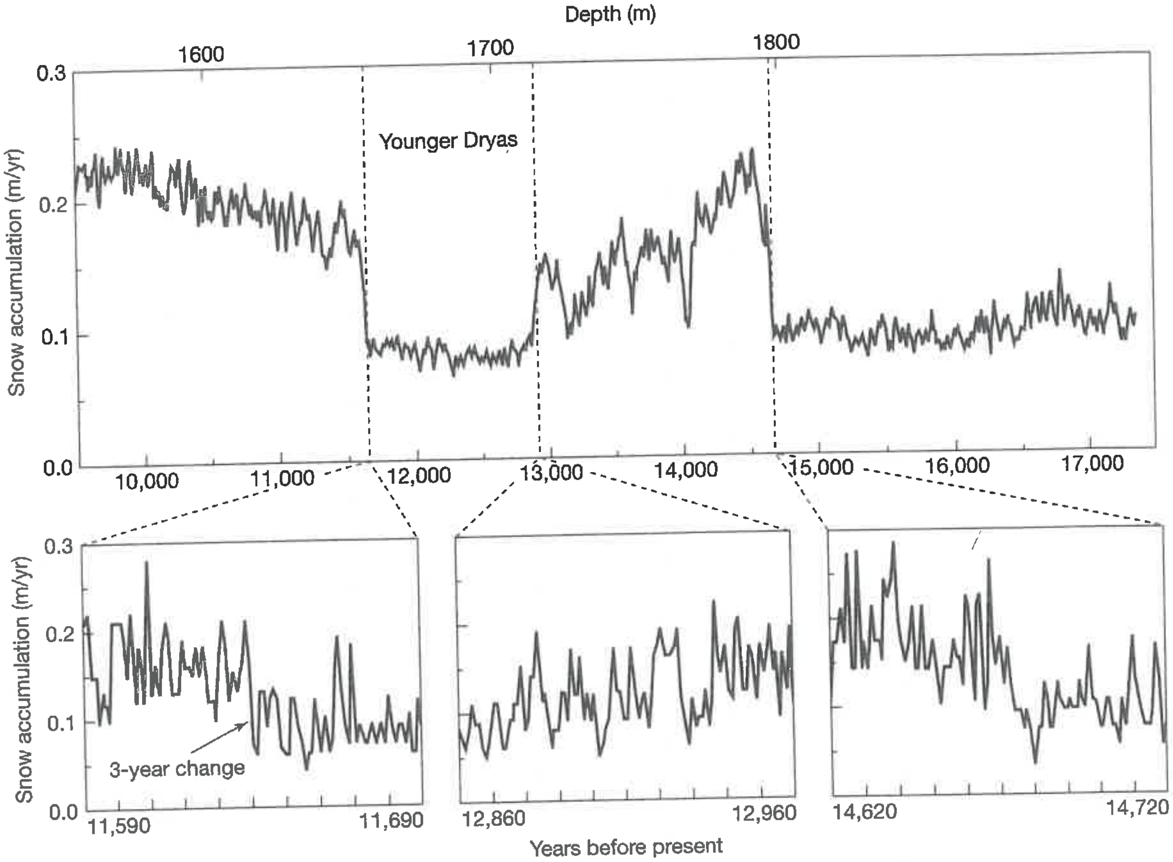


FIGURE 14-20 The snow accumulation record from a Greenland ice core. (*Source:* R. Alley et al. "Abrupt Increase in Greenland Snow Accumulation at the end of the Younger Dryas Event" *Nature* 362, 1993, pp. 527–529.)

We can view the climate system as having two (or more) stable steady states: glacial and interglacial, with the transition between the two representing the bifurcation point (see Figure 14-8). When the climate system is near the bifurcation point (e.g., at the end of the last glaciation), the system is unstable and any number of small perturbations could be amplified through positive feedbacks to push the system rapidly toward one stable state or the other. This possibility leads us to the second reason why the Greenland ice-core data have generated considerable interest. If these data do indicate that climate can switch rapidly between two very different stable states after a relatively small perturbation, a new wrinkle is added to the greenhouse warming question: If increased greenhouse gases should lead to a rapid shift in the climate system (possibly to a third, much warmer, quasi-equilibrium state), then our expectations of global warming (discussed in Chapters 15 and 16) may significantly underestimate the strength and the speed of the climate response to greenhouse forcing (see the Box "A Closer Look: Stochastic Resonance and Rapid Climate Change").

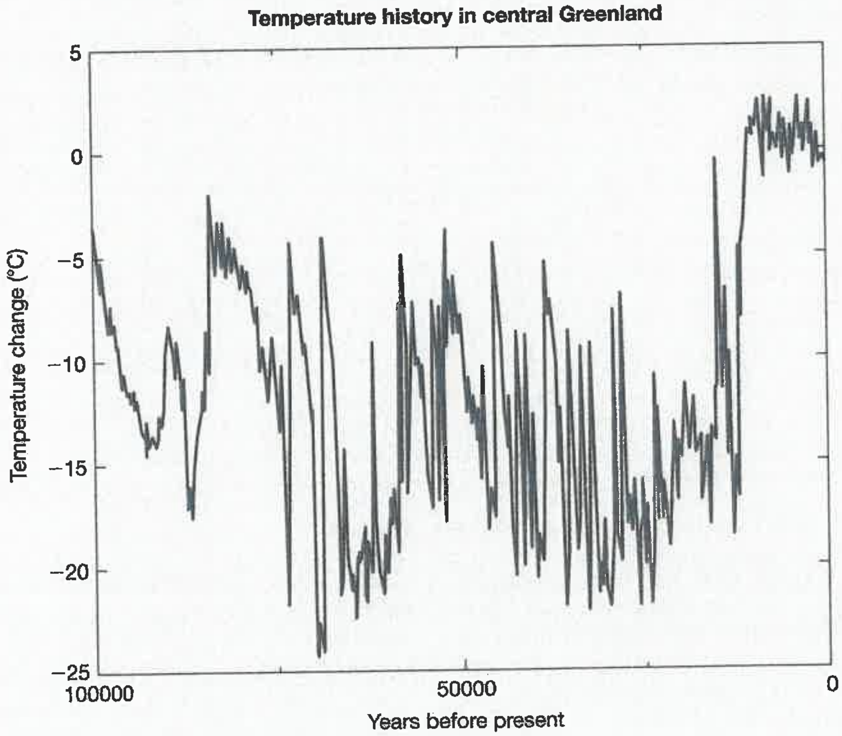
As our discussion turns to the issues of short-term climate change, both natural and anthropogenic, we must not forget that we are living in a time of unparalleled sensitivity of the climate system. The rapid climate shifts that Earth has experienced in its most recent geologic past caution us that tampering with the climate system might result in unexpectedly large climate responses. Furthermore, a prediction of future climate based solely on the Milankovitch forcing indicates that Earth should soon (geologically speaking) slip into the next glaciation. But, as a result of fossil-fuel burning and its effect on atmospheric CO_2 levels, it is not at all clear that this will be the case. We will draw on our knowledge of paleoclimates in subsequent chapters to make a more informed prediction of the future climates of Earth.

A CLOSER LOOK

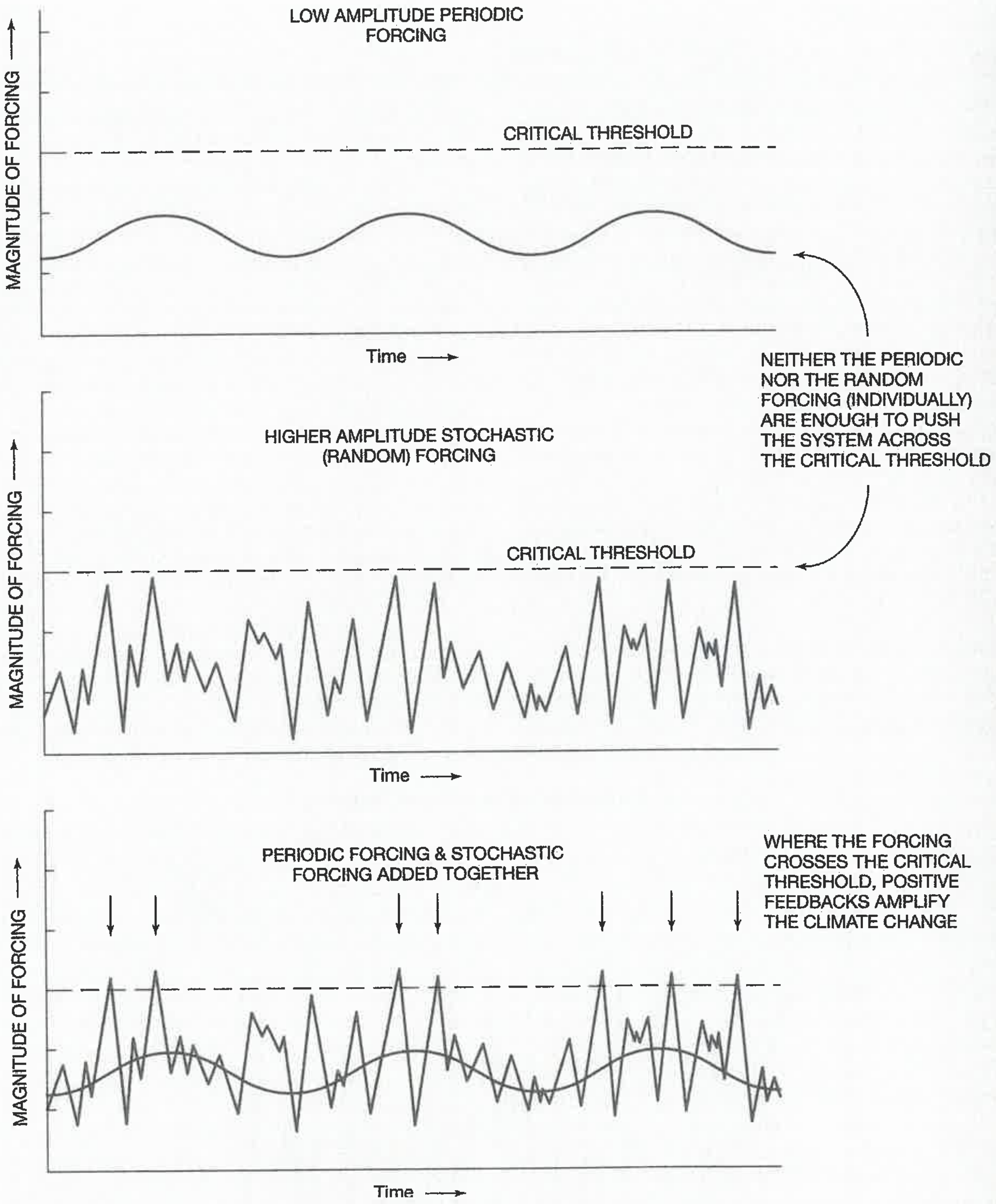
Stochastic Resonance and Rapid Climate Change

In the text we describe the rapid climate shift back into the Younger Dryas that occurred as the climate was warming from the last glacial maximum. We also explained how this could come about through shutting down the thermohaline circulation in the North Atlantic, followed by feedback processes that reduce atmospheric CO_2 concentrations. If we look in a little more detail at the climate record, however, we see that rapid climate changes such as these are actually very common (Box Figure 14-3). The temperature record from central Greenland (ice-core data) reveals large swings in climate during the last glaciation. Warm episodes punctuate the generally cold conditions and, as we move out of the glaciation, we see the system gradually warming then suddenly dropping back into cold conditions, warming, and dropping back again. Some of these rapid cooling events are accompanied by the flooding of the North Atlantic with glacial meltwater as described in the text, but many of them are not. Some appear to be random, while others appear to be periodic. Nothing we have discussed in the text really accounts for the behavior that we see here. One explanation that is gaining in popularity is the concept of stochastic resonance. Looking at the temperature record up until the start of the Holocene we see the characteristics of what is referred to by physicists as an "excitable system"—a system that has a stable and an unstable mode. It appears that there is a preferred "cold" mode and an unstable warm mode that the system cannot occupy for long.

Imagine a very weak but periodic forcing. This could, for example, be a very small change in solar output that occurs on a regular cycle, but is too weak to promote a significant change in climate. Superimposed on this are random variations that are inherent in the climate system. Taken together, these push the system across a threshold, and then what we need is a mechanism that can amplify the signal (Box Figure 14-4). The most likely mechanism that we can come up with at present is a change in the thermohaline circulation. It doesn't have to be anything as dramatic as shutting it down—maybe just a change in the location of the bottom water formation. What we then have is a situation with a stable cold mode (during the glaciation) with random perturbations (the "stochastic" part of stochastic resonance). At periodic intervals some other forcing gives a very weak push to the system, which "resonates" with the random variations and pushes the forcing beyond a critical threshold. At that point the change is amplified by the amplification mechanism (maybe ocean circulation) and pushes the climate into an unstable warm mode. The climate stays in this mode for a short interval before dropping back into the stable cold mode again. Analysis of the ice-core data by Richard Alley



BOX FIGURE 14-3 Temperature reconstruction for central Greenland based on ice-core data. Very large fluctuations have been common except recently. (*Source:* Courtesy Richard Alley, Pennsylvania State University.)



BOX FIGURE 14-4 Schematic representation of stochastic resonance.

and colleagues (see text) indicates that there is indeed a periodic forcing that occurs at an interval of about 1,500 years that accounts for much of the variation in the temperature record.

As we move out of the glacial episode, the reverse seems to happen. Now the system is warming up but we have sudden events like the meltwater release to the North Atlantic that temporarily pushes the climate back into a cold mode again. Where does this leave us? Climate scientists are looking at these ideas and asking, if these are correct, where does the periodic forcing come from? What is the amplification mechanism—is there more than one? Can the same thing happen during interglacials, when the planet seems to be in a more stable warm mode? Is there some other altogether different process waiting to be discovered that would explain what we see in the record? All of these are interesting questions, but why this is truly worth a closer look in the context of this text is because the climate record clearly shows that rapid and large changes do occur that are essentially unpredictable. It also shows that as the system is transitioning between states (i.e., as Earth was warming coming out of the last glaciation) it is common for it to be pushed back in the other direction very rapidly. Neither of these possibilities is taken into account in any of the projections currently put forward for global warming. While Chapter 15 describes what we can project ahead in terms of global warming, at the back of your mind you should keep note of the fact that processes such as those described here have the potential to surprise us—and completely change the magnitude (and maybe even direction) of the changes we predict for the future.

Chapter Summary

1. Earth's climate has varied on a number of time scales, from decadal to millennial changes we can directly observe to the billion-year evolution drive by solar evolution.
2. The best documented of these changes are those that occurred on intermediate time scales during the glacial cycles of the Pleistocene.
3. Substantial, periodic swings in climate over the past 2 million years are indicated by the geologic record of glacial deposits and by the oxygen isotopic record of global temperature and of continental ice-sheet volume.
4. Orbital (Milankovitch) theory provides the answer to the question of causation of glacial–interglacial cycles.
   a. Small changes in the configuration of Earth's orbit around the Sun, varying in a predictable fashion, have provided the slight changes in seasonal insolation necessary to initiate these climate swings. These include changes in orbital eccentricity, obliquity, and the precession of the spin axis.
   b. The climate response matches the relative magnitude of the forcing at the frequencies of the precessional and obliquity changes.
   c. However, the dominant periodicity of glacial–interglacial fluctuation is 100,000 years. The forcings from eccentricity changes at this periodicity are too small.
5. The climate system seems to have amplified the 100,000-year signal preferentially, through feedbacks involving the dynamics of continental ice sheets, the albedo of ice and clouds, and the controls on marine productivity and the growth of coral reefs and thus also on the cloud albedo and greenhouse effect.
6. As Earth warmed up from the effects of the last glaciation, a sudden and very rapid climate reversal occurred (the Younger Dryas event), resulting in the readvance of ice sheets and glaciers over much of northern Europe and other parts of the globe.
   a. Several hypotheses have been proposed to explain the Younger Dryas, the most likely of which involves the switching on and off of the thermohaline circulation in the North Atlantic Ocean.
   b. Regardless of the exact cause of this shift in climate, the Younger Dryas is of particular interest because recent ice-core data show that the change occurred very rapidly, over years to decades; the apparent ability of the climate system to shift rapidly between two very different states poses some interesting questions about how the climate may respond to future greenhouse warming.

Key Terms

aphelion
continental shelves
eccentricity
glacial
glacial striations
Holocene epoch
interglacial
loess
methane sulfonic acid (MSA)
moraine
obliquity
perihelion
period
Pleistocene epoch
precession
seasonal temperature contrast
stochastic resonance
till
Younger Dryas

Review Questions

1. What types of geologic evidence are diagnostic of glaciation?
2. What causes changes in the oxygen isotopic composition of seawater?
3. Which three characteristics of Earth's orbit around the Sun vary on the time scale of Pleistocene glaciations? How does each of these affect the amount of energy received from the Sun?
4. What orbital configuration favors glaciation? Why?
5. How is the oxygen isotopic record of marine limestones used to test Milankovitch's theory of the ice ages?
6. What role do biologically produced sulfur gases play in glacial climate fluctuations?
7. What factors might have caused atmospheric CO_2 variations that kept pace with glacial climate fluctuations?
8. Explain why the formation of North Atlantic Deep Water might have played a role in causing the Younger Dryas event.

Critical-Thinking Problems

1. Return to our Daisyworld analogy from Chapter 2. Construct a Daisyworld-like model of the MSA-climate feedback loop shown in Figure 14-19. First sketch a graph of how DMS production by algae would affect global temperature. Then sketch another graph of your view of how changes in global temperature might affect algal DMS production. Defend both graphs in writing. Then combine these graphs and discuss the stability of the equilibrium states indicated.
2. An ellipse is defined as the locus of all points such that the sum of the distances to two fixed points, called the foci, is a constant. We can easily show that this constant is equal to $2a$, where a is the semimajor axis of the ellipse. (See Box Figure 14-1 and the accompanying discussion.) The eccentricity e of the ellipse is defined such that the distance from one focus to the midpoint of the figure is ae. An ellipse with $e = 0$ is a circle.
   a. Kepler's first law states that the planets move around the Sun in elliptical orbits with the Sun at one focus. Earth's present orbit has a semimajor axis of 1 AU and an eccentricity of 0.017. The point of closest approach to the Sun is the perihelion; the point farthest away is the aphelion. How much closer is Earth to the Sun at perihelion than at aphelion? Express your answer in astronomical units.
   b. The Milankovitch theory of the ice ages holds that the most important forcing factor is the difference in solar heating at high latitudes when Northern Hemisphere summer occurs at perihelion as opposed to aphelion. Using the inverse square law (Chapter 3), find the solar flux at perihelion and at aphelion. Recall that the solar flux at 1 AU is 1370 Watts/m^2. How much higher is the solar flux at perihelion than at aphelion today? Express your answer as a percentage. How much warmer is the effective radiating temperature of Earth (Chapter 3)?
   c. The eccentricity of Earth's orbit varies with time as a consequence of gravitational perturbations caused by the other planets. Repeat Problem 2b for e at its maximum value of 0.06.
   d. Kepler's third law states that the square of a planet's period P is proportional to the cube of its semimajor axis a. When P is expressed in Earth years and a is in AU, the relationship is simply $P^2 = a^3$. Venus and Mars have semimajor axes of 0.72 and 1.52 AU, respectively. How many Earth years does it take for them to go around the Sun?

Further Reading

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