Reconstructing Ice-Age Ocean-Surface Conditions

The upper parts of drill cores taken from the seafloor throughout the world's oceans consist of soft sediments that commonly contain multitudes of tiny fossils. Most of the fossils are of microorganisms that live in the surface waters and whose shells rain down on the seafloor in vast numbers to form deep-sea oozes (Chapter 11). The rate of sedimentation is extremely slow, however, so that it may take more than a thousand years for a single centimeter of sediment to accumulate. Because the assemblage of organisms that live in the surface waters is closely related to water temperature, the fossil remains in the sediment provide a record of changing conditions at the ocean surface.

In many deep-sea sediment cores, the fossil content changes downward, typically shifting back and forth from predominantly warm-water (interglacial) to cold-water (glacial) forms. By identifying the species present at any
tended far south of its present limit in the North Atlantic, and plumes of cool water extended westward from South America in the equatorial Pacific and from Africa in the Atlantic.

Figure C14.1 Present and past temperatures of surface waters in the world ocean. A. Map showing modern August sea-surface temperatures (in °C). B. Map showing reconstructed August sea-surface temperatures during the last glaciation, about 18,000 years ago. Cold polar water ex-

3. By obtaining measurements of the oxygen-isotope ratio in ice cores that penetrate ice of the last glacial age (Fig. 14.7), former surface air temperature can be estimated. The measurements show a marked change in isotope values at a level coinciding with the transition from mild (Holocene) interglacial climate recorded in the upper parts of the cores to cold ice-age temperatures below.

4. By noting the distribution of certain periglacial features that indicate former permafrost conditions, an estimate can be made of the minimum temperature change that has taken place. At present, permafrost exists mainly in areas where the
level in a sediment core and comparing that assemblage with modern ones, it is possible to infer what the surface ocean temperature must have been when the shells were settling to the seafloor. In practice, geologists can select a level in a core that represents the peak of the last glaciation and determine, from the contained fossils, the surface water temperature at that time. Information from hundreds of cores scattered widely over the oceans has been used to derive a global map of sea-surface temperature for the last glacial maximum (Fig. C14.1B).

Surprisingly, the average global difference between present and ice-age sea surface temperatures is only about 2.3°C (4°F), but this figure is somewhat misleading. In some large regions, like the subtropics, little or no change in temperature is detected. In others, such as the North Atlantic, sea-surface temperatures were locally as much as 14°C (25°F) colder than now. In this region, cold polar water that is now found mainly north of latitude 60° descended far south as the peak of the glaciation to reach the shore of northeastern United States and the Iberian Peninsula in western Europe.

The greatest ocean temperature declines occurred in the North Atlantic around which large continental ice sheets were located, and in enclosed seas of the northwestern Pacific. They also were substantial near the equator, where cold water that welled up off the coasts of Africa and South America spread westward across the equatorial Atlantic and Pacific, respectively. However, over vast areas within the North and South Pacific midocean gyres, sea-surface temperatures apparently changed very little.

![Map of Last Glaciation](image)

Mean annual air temperature is below −5°C (23°F). If, for example, evidence of former permafrost is found at a place where the annual temperature is now 4°C (39°F), then the former periglacial climate is inferred to have been at least 9°C (16°F) colder.

5. By sampling deep-sea sediment cores for fossils of microorganisms that lived near the ocean surface and by comparing the fossil assemblages with those now living in surface waters at various latitudes, sea-surface temperatures during the last glaciation can be reconstructed (see "A Closer Look: Reconstructing Ice-Age Ocean-Surface Conditions").
From these and other types of evidence obtained on land and from the oceans, we have learned an important fact: the changes accompanying a shift from interglacial to glacial conditions did not affect the whole world equally. The environments of some regions apparently changed little if at all, whereas others experienced profound changes.

**Successive Pleistocene Glacial and Interglacial Ages**

As recently as a few decades ago, it was thought that the Earth had experienced only four glacial ages during the Pleistocene Epoch. This assumption was based on studies of ice sheet and mountain glacier deposits, and it had its roots in early studies of the Alps where geologists identified stream terraces they thought were related to four ice advances. This traditional view was discarded when studies of deep-sea sediments disclosed a long succession of glaciations during the Pleistocene, the most recent of which was shown by radiocarbon dating to outlast deposits of the last glaciation on the continents. Paleomagnetic dating (Chapter 6) of deep-sea cores shows that the most recent glacial-interglacial cycles recorded in the sediments average about 100,000 years long and that during the last 800,000 years alone there have been about eight such episodes. For the Pleistocene Epoch as a whole (the last 1.8 million years), about 30 glacial ages are recorded rather than the traditional four. The implications are clear: whereas seafloor sediments provide a continuous historical record of climatic change, evidence of glaciation on land generally is incomplete and interrupted by many unconformities.

The seafloor evidence is of three kinds. First, with increasing depth in a core, the biologic component of the sediments shows repeated shifts from warm interglacial biota to cold glacial biota. Second, the percentage of calcium carbonate in cores from some ocean regions fluctuates in much the same manner. Third, the $^{18}O$ to $^{16}O$ isotope ratio fluctuates with a pattern similar to that seen in the biologic and mineral fractions of the sediments. Whereas the isotopic variations in ice cores are believed to represent fluctuations in air temperature near the glacier surface, in Pleistocene marine sediments they are thought primarily to reflect changes in global ice volume. During glacial ages, when water is evaporated from the oceans and precipitated on land to form glaciers, water containing the light isotope $^{16}O$ is more easily evaporated than water containing the heavier $^{18}O$. As a result, Pleistocene glaciers contained more of the light isotope, whereas the oceans became enriched in the heavy isotope. Isotope curves derived from the sediments therefore give us a continuous reading of changing ice volume on the planet (Fig. 14.16). Because glaciers wax and wane in response to changes in climate, the isotopes also give a generalized view of global climatic change.

Figure 14.16  Curve of average oxygen-isotope variations during the last 2 million years based on analyses of deep-sea sediment cores. The curve illustrates changing global ice volume during successive glacial-interglacial cycles of the Quaternary Period.

For most of the last 800,000 years, peaks in the isotope curve that represent times of high global ice volume have a somewhat similar amplitude, suggesting that during each glacial the amount of ice on land was about the same (Fig. 14.16). During this long interval, the average length of a glacial-interglacial cycle was about 100,000 years. Prior to that time, however, the amplitude of the cycles was smaller and their duration averaged only about 40,000 years. Why the cycle length changed is not yet known with certainty, but it
clearly represents a fundamental shift in the Earth's climate system.

A record of ocean-surface temperatures, based on oxygen isotopic values in deep-sea cores that penetrate Cenozoic sediment, shows that the oceans have grown colder over the last 50 million years (Fig. 14.17). During one pronounced cooling event about 35 million years ago, surface ocean temperatures declined by nearly 5°C (9°F) within only about 100,000 years. In concert with the long-term cooling trend, glaciers spread from highlands in Antarctica and reached the sea. About 12 to 10 million years ago, ice volume increased, and an ice sheet formed over Antarctica as temperatures continued to fall. The presence of such a large polar ice mass reduced average temperatures on the Earth still further and caused a substantial drop in sea level. From that time onward, large glaciers occupied mountain valleys of Alaska and the southern Andes. Although the evidence is still sketchy, it appears that large ice sheets did not form in northern middle latitudes until about 2.5 million years ago. If this inferred history is correct, glaciation has gradually affected more and more of the Earth's land surface during the Cenozoic: first the Antarctic, then high-latitude mountain systems, and more recently the northern middle latitudes.

Ancient glaciations, identified mainly by rocks of glacial origin and associated polished and striated rock surfaces, are known from pre-Cenozoic times as well. The earliest recorded glacial episode dates to about 2.3 billion years ago, in the middle Precambrian. Evidence of other glacial episodes has been found in rocks of late Precambrian, early Paleozoic, and late Paleozoic age (Fig. 8.3). During the latest of these intervals, 50 or more glaciations are believed to have occurred. The geologic record is fragmentary and not always easy to interpret, but evidence from such low-latitude regions as South America, Africa, and India, as well as from Antarctica, suggests that the Earth's land areas must have had a very different relationship to one another during the late Paleozoic glaciation than they do today. In the Mesozoic Era, glaciation of similar magnitude apparently did not occur, consistent with geologic evidence that points to a long interval of mild temperatures both on land and in the oceans.

The Warm Middle Cretaceous

It's probably a good thing we did not live 100 million years ago during the Middle Cretaceous Period. Not only was the world inhabited by huge carnivorous dinosaurs, but also the climate was one of the warmest in the Earth's history. Evidence that the world was much warmer in that period than it is today is compelling (Fig. 14.18). Warm-water marine faunas were widespread, coral reefs grew 5° to 15° closer to the poles than they do now, and vegetation zones were displaced about 15° poleward of their present positions. Peat deposits that would give rise to widespread coal formations formed at high latitudes, and dinosaurs, which are generally thought to have preferred warm climates, ranged north of the Arctic Circle. Sea level was 100 to 200 m (330 to 650 ft) higher than today, implying the absence of polar ice sheets, and isotopic measurements of deep-sea deposits indicate that intermediate and deep waters in the oceans
were 15° to 20°C (27° to 36°F) warmer than now. Based on such evidence, average global temperature is estimated to have been at least 6°C (11°F) milder than today and possibly as much as 14°C (25°F), with the greatest difference being in the polar regions. Whereas today the difference in temperature between the poles and the equator is 41°C (74°F), during the Middle Cretaceous it may have been no more than 26°C (47°F) and possibly as little as 17°C (31°F).

Computer simulations of past climates provide insights into the Middle Cretaceous world and suggest that several factors were likely involved in producing such warm conditions: geography, ocean circulation, and atmospheric composition. The simulations show that the Middle Cretaceous arrangement of continents and oceans (Fig. 14.18), which influenced ocean circulation and planetary albedo, could account for nearly 5°C (9°F) of warming. Of this 5°C, about a third is attributable to the absence of polar ice sheets. However, geography alone is inadequate to explain warmer year-round temperatures at high latitudes. Could the poleward transfer of heat be the answer? The oceans now account for about a third of the present poleward heat transfer, but modeling shows that even with the geography and ocean circulation rearranged as they were in the Middle Cretaceous, oceanic heat transfer cannot explain the greater high-latitude warmth. If the geologic data have been correctly interpreted, and the modeling results are reliable, some other factor must be involved. This factor appears to be CO₂, the major greenhouse trace gas (Chapters 19 and 20).

The model simulations show that, by rearranging the geography and also increasing carbon dioxide six to eight times above present concentrations, the warmer temperatures can be explained. Geochemical reconstructions of changing atmospheric CO₂ levels over the past 100 million years point to at least a tenfold increase in CO₂ during the Middle Cretaceous, leading to average temperatures as much as 8°C (14°F) higher than now (Fig. 14.19). Under such conditions, it is easy to see why ice volume on the Earth was unusually low and world sea level was so high.

**WHY CLIMATES CHANGE**

What factors cause the climate to warm and cool, bringing about great changes in the Earth's surface processes and environments? The search for an answer has proved difficult because climate fluctuates on different time scales, ranging from decades to many millions of years, and several quite different mechanisms appear to be responsible for these changes. Furthermore, these mechanisms involve not only the atmosphere, but also the lithosphere, the oceans, the biosphere, and extraterrestrial factors, all interacting
in a complex way. The search for causes of climatic variability is therefore a challenging one.

Glacial Eras and Shifting Continents

The only reasonable explanation for a succession of glacial episodes during the last 2.3 billion years seems to be the slow but important geographic changes that affect the Earth's crust. These changes include the movement of continents as they are carried along with shifting plates of lithosphere, the creation of high mountain chains and plateaus where plates collide, and the opening or closing of ocean basins and seaways between moving landmasses.

How such movements affect climate is illustrated by the fact that low temperatures occur, and glaciers tend to form and persist, in high latitudes and at high altitudes, and especially in places where winds can supply abundant moisture evaporated from a nearby ocean. The Earth's largest existing glacier is centered on the South Pole, where temperatures are constantly below freezing and the land is surrounded by ocean. The only glaciers found at or close to the equator lie at extremely high altitudes.

Abundant evidence now leads us to conclude that the positions, shapes, and altitudes of landmasses have changed with time (Chapter 4). In the process, the path of ocean currents and atmospheric circulation have been altered. As landmasses and ocean basins have shifted position, occasionally they have assumed an arrangement that was optimal for widespread glaciation in high latitudes. Where evidence of ancient ice sheet glaciation is found in low latitudes, we invariably find evidence that such lands formerly were located in higher latitudes. Although this explanation appears adequate to explain the pattern of glaciation during and since the late Paleozoic, information about earlier glacial intervals is very fragmentary and more difficult to evaluate.

Why Was the Middle Cretaceous Climate So Warm?

Interspersed with ancient glacial intervals were episodes of exceptionally warm climate, like that of the Middle Cretaceous. If CO₂ was an important factor in Middle Cretaceous warming, as suggested earlier, we still are faced with explaining how this gas increased so substantially. A likely explanation is volcanic activity, which today constitutes a major natural source of CO₂ entering the atmosphere. Most of this CO₂ is generated by slow, noneruptive degassing of magmas in the upper crust.

Geologic evidence points to an unusually high rate of volcanic activity in the Middle Cretaceous. Rates of continental drift were then about three times as great as now, implying increased eruption rates at spreading ridges. In addition, vast outpourings of lava created a succession of great undersea volcanic plateaus across the southern Pacific Ocean between 135 and 115 million years ago, the time of maximum Cretaceous warmth. One of these—the Ontong Java Plateau in the southeastern Pacific—has more than twice the area of Alaska and reaches a thickness of 40 km (25 mi). Such a massive outpouring of lava likely released a huge volume of CO₂. Could this gas emission have been sufficient to warm the climate to unprecedented levels? By one calculation, the eruptions could have released enough CO₂ to raise the atmospheric concentration to 20 times its natural value at the beginning of the Industrial Revolution (ca. a.d. 1760), in the process raising average global temperature as much as 10°C (18°F). Other estimates range from 8 to 12 times the a.d. 1760 value.

Recently, geologists have proposed that each such vast lava outpouring is associated with a superplume, which is conceived of as a plume-like mass of unusually hot rock that rises from the base of the mantle. Moving upward at a rate of 10 to 20 cm/yr (4 to 8 in/yr), the hot rock spreads out in a mushroom shape as it reaches shallower depths where confining pressures are lower (Fig. 14.20). Such a superplume would be an efficient mechanism for allowing heat to escape from the Earth's core. If this hypothesis is correct, then the plate tectonic cycle could study the mantle both by heat loss at spreading ridges and by the outward plunge of plates of cool lithosphere, while superplumes cool the core. By this reasoning, the core and atmosphere are linked dynamically, and the warm Middle Cretaceous climate was a direct consequence of the cooling of the Earth's deep interior.

Ice-Age Periodicity and the Astronomical Theory

Determining the cause of the cyclic pattern of glacial and interglacial ages has long been a fundamental challenge to the development of a comprehensive theory of climate. A preliminary answer was provided by Scottish geologist John Croll, in the mid-nineteenth century, and later elaborated by Milutin Milankovitch, a Serbian astronomer of the early twentieth century.

Croll and Milankovitch recognized that minor variations in the Earth's orbit around the Sun and in the tilt of the Earth's axis cause slight but important variations in the amount of radiant energy reaching...
any given latitude. Three movements are involved (Fig. 14.21).

First, the axis of rotation, which now points in the direction of the North Star, wobbles like the axis of a spinning top (Fig. 14.21A). The wobbling movement causes the North Pole to trace a cone in space, completing one full revolution every 26,000 years. At the same time, the axis of the Earth’s elliptical orbit is also rotating, but much more slowly, in the opposite direction. These two motions together cause a progressive shift in the position of the four cardinal points of the Earth’s orbit (spring and autumn equinoxes and winter and summer solstices). As the equinoxes move slowly around the orbital path, a motion called precession of the equinoxes, they complete one full cycle in about 23,000 years.

Second, the tilt of the axis, which now averages 23.5°, shifts about 1.5° to either side during a span of about 41,000 years (Fig. 14.21B).

Finally, the eccentricity of the orbit, which is a measure of its circularity, changes over a period of 100,000 years. About 50,000 years ago, the orbit was more circular (lower eccentricity) than it has been for the last 10,000 years (Fig. 14.21C).

The slow but predictable changes in precession, tilt, and eccentricity cause long-term variations of as much as 10 percent in the amount of radiant energy that reaches any particular latitude on the Earth’s surface in a given season (Fig. 14.22). By reconstructing and dating the history of climatic variations over hundreds of thousands of years, geologists and oceanographers have shown that fluctuations of climate on glacial-interglacial time scales match the predictable cyclic changes in the Earth’s orbit and axial tilt. This persuasive evidence supports the theory that astronomical factors control the timing of the glacial-interglacial cycles.

**Amplification of Temperature Changes**

Although orbital factors can explain the timing of the glacial-interglacial cycles, the variations in solar radiation reaching the Earth’s surface are too small to account for the average global temperature changes of 4 to 10°C (7 to 18°F) implied by paleoclimatic evidence. Somehow, the slight temperature decreases caused by orbital changes must have been amplified into temperature changes sufficiently large to generate and maintain the huge Pleistocene ice sheets. We do not yet know how this amplification was accomplished, but some of the factors involved are likely to be changes in the chemical composition and dustiness of the atmosphere and changes in the reflectivity of the Earth’s surface.

The chemical composition of air bubbles trapped in polar glaciers indicates that during glacial times the atmosphere contained less carbon dioxide and methane than it does today (Fig. 14.23). These two gases are important greenhouse gases (Chapter 20). If their concentration in the atmosphere is high, they trap radiant energy emitted from the Earth’s surface that would otherwise escape to outer space. As a result, the lower atmosphere heats up and the Earth’s climate becomes warmer. If the concentration of these
gases is low, as it was during glacial times, surface air temperatures are reduced. Calculations suggest that the low levels of these two important atmospheric gases during glacial times can account for nearly half of the total ice-age temperature lowering. Therefore, the greenhouse gases likely played an important role in explaining the magnitude of past global temperature changes. Although we know that the atmospheric concentration of these gases fell during glacial times, we do not yet know for certain what caused them to fall.

As we learned earlier, ice core studies have shown that the amount of dust in the atmosphere was unusually high during glacial times when mid-latitude climates were generally drier and windier. The fine atmospheric dust scattered incoming radiation back into space, which would have further cooled the Earth’s surface.

Whenever the world enters a glacial age, large areas of land are progressively covered by snow and glacier ice, and the extent of high-latitude sea ice increases. The highly reflective surfaces of snow and ice scatter incoming radiation back into space, further cooling the lower atmosphere. Together with lower greenhouse gas concentrations and increased atmospheric dust, this additional cooling would favor the expansion of glaciers.

**Changes in Ocean Circulation**

As we discussed in Chapter 11, the circulation of the world ocean plays an important role in global climate. The thermohaline circulation system links the atmosphere with the deep ocean. Warm surface water moving northward into the North Atlantic evaporates, and the remaining water becomes more saline and cools.

**Figure 14.21** Geometry of the Earth’s orbit and axial tilt.

A. **Precession.** The Earth wobbles on its axis like a spinning top, making one revolution every 26,000 years. The axis of the Earth’s elliptical orbit also rotates, though more slowly, in the opposite direction. These motions together cause a progressive shift, or precession, of the spring and autumn equinoxes, with each cycle lasting about 23,000 years.

B. **Tilt.** The tilt of the Earth’s axis, which now is about 23.5°, ranges from 21.5° to 24.5°. Each cycle lasts about 41,000 years. Increasing the tilt means a greater difference, for each hemisphere, between the amount of solar radiation received in summer and that received in winter.

C. **Eccentricity.** The Earth’s orbit is an ellipse with the Sun at one focus. Over 100,000 years, the shape of the orbit changes from almost circular (low eccentricity) to more elliptical (high eccentricity). The higher the eccentricity, the greater the seasonal variation in radiation received at any point on the Earth’s surface.
Figure 14.22 Curves showing variations in eccentricity, tilt, and precession during the last 800,000 years. Summing these factors produces a combined signal that shows the amount of radiation received on the Earth at a particular latitude through time. The magnitude and frequency of oscillations in the combined orbital signal closely matches those of the marine oxygen isotope curve (on right), which supports the theory that the Earth's orbital changes control the timing of the glacial-interglacial cycles.

Figure 14.23 Curves comparing changes in carbon dioxide and methane with temperature changes based on oxygen-isotope values in samples from a deep ice core drilled at Vostok Station, Antarctica. Concentrations of these greenhouse gases were high during the early part of the last interglaciation, just as they are during the present interglaciation, but they were lower during glacial times. The curves are consistent with the hypothesis that the atmospheric concentration of these gases contributed to warm interglacial climates and cold glacial climates.
The resulting cold, saline water is dense and sinks to produce cold North Atlantic Deep Water. Heat released to the atmosphere by evaporation maintains a relatively mild interglacial climate in northwestern Europe. Consider what would happen, however, any time this system closed down.

The rate of thermohaline circulation is sensitive to surface salinity at sites where deep water forms. Studies have shown that during times of reduced salinity, thermohaline circulation is also reduced. Therefore, we can postulate that as summer radiation decreased at the onset of a glaciation, the high latitude ocean and atmosphere cooled, decreasing evaporation and leading to expansion of sea ice. The resulting decreased salinity of the high-latitude surface waters would have halted the production of dense saline water, thereby shutting off thermohaline circulation. Reduction of high-latitude evaporation, significantly reducing the release of heat to the atmosphere, would have maintained cold air masses moving eastward across the North Atlantic. Further cooled by an expanding sea-ice cover in the North Atlantic and extensive ice sheets on the adjacent continents, the climate of Europe became increasingly cold, causing permafrost to form in a broad zone beyond the ice sheet margin (Fig. 14.10).

Thus, a change in the ocean's thermohaline circulation system provides a means of further amplifying the relatively small climatic effect attributable to astronomical changes. Furthermore, it may help explain why the Earth's climate system appears to fluctuate between two relatively stable modes, one in which the ocean conveyor system is operational (interglaciation) and one in which it has shut down (glaciation).

**Millennial-Scale Changes of Climate**

Over the past decade, considerable interest has been focused on fluctuations of climate that have occurred at intervals of several thousand rather than tens of thousands of years. Such changes are clearly displayed in isotope records from deep-sea cores, and they also have been detected in pollen, loess, lake-sediment, ice-core, and glacial records on land. The climatic changes are of interest because they are relatively brief (commonly lasting only a few hundred to a thousand years) and their onset and termination are often rapid, even abrupt. Detailed studies of ice cores have shown that the shift from one climate state to another may take no more than a few decades, or less than a human lifespan. Furthermore, some changes have been so large as to suggest that the climate oscillated in and out of full-glacial conditions during much of the last glacial age. Clearly, we need to learn the causes of these changes if we are to understand the global climate system.

An important clue came with the recognition of discrete layers of ice-rafted sediment layers in the upper parts of deep-sea cores from the North Atlantic Ocean. Referred to as Heinrich layers, after the marine geologist who first described them, they record sudden discharges of icebergs into the North Atlantic from the surrounding continental ice sheets during the last glaciation. Six main layers, designated H1 through H6, occurred within the interval spanning the last 70,000 years (Fig. 14.24). The discharges of icebergs led to deposition of coarse sediment on the seafloor as the bergs melted, producing the distinct layers of ice-rafted detritus (IRD). Decreased concentrations of the skeletal remains of surface-dwelling foraminifera at the level of the IRD layers in these cores show that the temperature of the ocean waters fell during the Heinrich events. Mineralogical studies have demonstrated that most of the debris layers originated in geologic regions then covered by the northeastern part of the largest North American ice sheet, and that debris in one layer (H3) likely originated in the Iceland-Scandinavian sector of the North Atlantic.

The climatic effects of the Heinrich events must have been profound and must have reverberated through key elements of the Earth's interacting atmosphere, hydrosphere, cryosphere, and biosphere systems. Air passing across the vast field of icebergs and cold low-salinity surface water associated with them was cooled as it swept eastward, causing temperatures to plummet in western Europe. There, the cold events are clearly recorded in lake sediments that show a shift to colder-climate vegetation assemblages during each event. The fact that similar climate shifts at these same times are found in pollen records from Florida, in loess deposits of China, and in alpine glacial deposits of western North America and South America implies that the Heinrich events affected climates worldwide. However, this raises the important question: how could icebergs in the North Atlantic affect climate globally?

The answer to this question most likely lies in the role of the Atlantic in the ocean's thermohaline circulation system. During a Heinrich event, a capping lid of cold meltwater laden with icebergs would have interrupted the generation of saline North Atlantic Deep Water, thereby shutting down the ocean conveyor system. Because that system affects the oceans worldwide (Fig. 11.13), world climate is also affected.

The large swings in climate associated with Heinrich events, and corresponding cooling events detected in the Greenland ice cores, appear to be a phe-
Figure 14.24  Layers of ice-rafted debris (IRD) in a sediment core spanning the last 80,000 years from the eastern North Atlantic Ocean (labeled H1-H6) record massive outbursts of icebergs from nearby ice sheets. Sediment in five of the layers likely originated in glacier-covered northeastern Canada, whereas one (H3) apparently was derived mainly from the Iceland-Scandinavia sector of the North Atlantic. Air masses passing across the floating ice and frigid surface ocean water were cooled as they swept toward western Europe, bringing cold temperatures to the region north of the glaciers that covered Scandinavia and the British Isles.

A phenomenon of glacial times, times when large ice sheets encircled the North Atlantic. Events of comparable magnitude are not seen in records postdating the last glaciation. Smaller-scale ice-rafting events, recurring every 2000 to 3000 years, also punctuate the record of the last glaciation. These events may represent iceberg discharges of smaller magnitude from local sources in Iceland and eastern Canada. Possibly they are related to changes in sea level that destabilized the marine margins of the circum-North Atlantic ice sheets.

Yet another cycle of climate variation has recently been recognized in the marine record, one that recurs about every 1500 years. These climate shifts occur during both glacial and interglacial times and therefore operate independently of the astronomically controlled glacial-interglacial cycles. Their cause is not yet known.

Solar Variations and Volcanic Activity

Climatic fluctuations measured in centuries or decades were responsible for the Little Ice Age and similar episodes of glacier expansion. However, such fluctuations are too brief to be caused either by movements of continents or variations in the Earth's orbit, and so require us to seek other explanations for their cause. Two explanations have received special attention.

One hypothesis regarding the cause of short-lived glacial events like the Little Ice Age is based on the concept that the energy output of the Sun fluctuates over time. The idea is appealing because it might explain climatic variations on several time scales. However, although correlations have been proposed between weather patterns and rhythmic fluctuations in the number of sunspots appearing on the surface of the Sun, as yet there has been no clear demonstration that solar variations are responsible for climatic changes on the scale of the Little Ice Age.

Large explosive volcanic eruptions can eject huge quantities of fine ash into the atmosphere to create a veil of fine dust that circles the globe (Chapter 7 opener). Like other types of dust, the fine ash particles tend to scatter incoming solar radiation, resulting in a slight cooling at the Earth's surface. Although the dust
Guest Essay

Is Our Climate Changing? Tree-ring Records Can Put Extreme Weather into Context

In the last several years, weather has moved from the back pages of our daily newspapers to the front-page headlines. During the winter of 1998, the most severe El Niño event of the twentieth century caused millions of dollars of storm-related damage in North America as well as drought-related crop failures in northeastern Brazil. Such events caused the "greenhouse effect" (see Chapter 18) to become a household term as citizens around the world debated whether human-induced changes in the composition of the atmosphere had significantly altered the Earth's climate. In the public's mind, the question emerges: What is happening to our weather? To the scientific community, a related question has gained widespread attention: Are these weather events a harbinger of large-scale climatic variation or simply a part of natural climatic variability?

These questions, though urgent, are not new. When I was in graduate school in the late 1970s, weather was also in the news. At that time, the west coast of the United States was experiencing its worst drought episode since the dust bowl years of the 1930s and the droughts were causing widespread famine in the Sahel of Africa. In my climatology classes, professors expressed dismay and articulated a question that has simultaneously haunted and intrigued me ever since: Are our weather records, which for most of the world extend back only to the early twentieth century, adequate to understand the complex dynamics of the climate system? As I puzzled over this question, one professor suggested that I might find an answer to that question by looking at the record of climate recorded in tree rings, a record that extends for several hundred, or, in some cases, several thousand years back in time. Acting on that suggestion, I began a life-long odyssey that has taken me to some of the most beautiful mountain ranges of the world in search of the old trees that are providing me the answers to current questions about climate change.

The field of tree-ring research, or dendrochronology, is based on several key concepts. During the growing season, trees produce xylem cells, specialized for the upward transport of water and nutrients, along the outermost circumference of the bole. Early in the growing season, the tree produces cells that are large, have thin walls, and appear light in color. Later in the growing season, the tree produces cells that are small, have thick walls, and appear dark in color. The distinctive alteration of light and dark cells marks a single annual growth ring, often visible to the naked eye when we examine a freshly cut stump. Luckily, tree-ring scientists do not have to cut down trees to study the patterns of the rings. We use a coring device that removes a core about the size of a pencil from the tree, a process that causes no damage to the tree. Back in the laboratory, we use a light microscope, interfaced with a computer-aided measuring device, to measure the right widths (see Fig. 14.8).

What do the tree rings tell us about the history of climate? If the tree is growing at a site characterized by cold temperatures and a short growing season (e.g., high-latitude or high-elevation sites), year-to-year variation in summer temperature will cause variation in the width of the ring. If the tree is growing at a semiarid site, variations in precipitation will cause variation in the width of the ring. In my own research, I use these different types of sites to obtain different types of climatic histories. When I sample spruce trees at the northernmost limit of tree growth in the Brooks Range of Alaska, the samples indicate the history of summer temperature fluctuations in the Arctic. Alternatively, my cores from juniper trees at the margins of the Gobi Desert, high on the Tibetan Plateau of China, allow me to reconstruct a 1600-year history of the fluctuating rainfall. Working with Dr. Lonnie Thompson and our Chinese colleague Dr. Yao Tandong, we are comparing the ice core and tree-ring records to understand the complex dynamics of Asian monsoons.

settles out rather quickly, generally within a few months to a year, tiny droplets of sulfuric acid, produced by the interaction of volcanically emitted SO2 gas and water vapor, also scatter the Sun's rays, and such droplets remain in the upper atmosphere for several years. The major eruptions of Krakatau (A.D. 1883) and Tambora (A.D. 1815) in the East Indies, and Pinatubo (1991) in the Philippines, lowered average surface temperatures in the northern hemisphere between 0.3 and 0.7°C (0.5 and 1.3°F). A far greater eruption of Toba volcano about 74,000 years ago, the largest known prehistoric explosive eruption, may have lowered surface temperatures in the northern hemisphere by 3 to 5°C (5 to 9°F).