CHAPTER 10

Climate change and the evolution of life

Climate changes and Earth history

Most life as we know it can exist only within a narrow range of temperatures, and changing climate has been a major driving force in the evolution of life on Earth. Historical and geological records show that the global temperature on Earth has fluctuated widely throughout history. On scales of hundreds of millions of years, the planet oscillated between warm intervals and major ice ages when the planet may have been entirely covered by ice. Within each major ice age, the climate record shows a regular advance and retreat of the ice sheets. In the shorter term our climate has been marked by relatively small changes in global temperature. Throughout history, climatic changes have determined the destiny of life, allowing certain life forms to flourish whilst others are pushed to extinction.

In this chapter we will look at the three major scales on which Earth's climate shows fluctuations. The occurrence of major ice ages is known to be connected to plate movements, which cause changes to the surface of Earth, and we will see how tectonics are directly involved in heating or cooling a planet. We will then move on to look at the causes of climate changes within each major ice age, which cause a regular advance and retreat of the ice sheets, and how this pattern is linked to Earth's orbit around the Sun. On a much shorter term, climate change has had significant effects on human activities, and direct measurement of temperatures has shown distinct trends. We will look at the causes of short-term climate change, both natural and human-related, and what might be in store for us in the future.

10.1 Timescales of climate change

Long-term climatic change shows fluctuations over tens to hundreds of millions of years. These long-term changes involve swings in global temperature of as much as 10 °C (about 20 °F). At the low points of these long-term cycles, ice sheets cover large areas of the planet. These times are known as *major ice ages*. At the high points of these fluctuations, Earth experiences long intervals when the entire planet is considerably warmer than at present, and large ice sheets are absent from the globe.

Within a major ice age, temperature fluctuations of roughly 6 °C (about 10 °F) occur in cycles of tens to hundreds of thousands of years. These variations produce *glacial* and *interglacial* periods, i.e., times within an ice age when ice sheets alternately advance and retreat across the continents.

Within a glacial or interglacial period, smaller changes of about 0.5 °C (1 °F) occur with timescales of about a hundred to a thousand years. Several such episodes of climatic change have been recorded in historic times. A shift of as little as 0.5 °C in the average temperature of the globe can have a significant impact on agriculture, transportation, and other human activities.

Previous page: Canada glacier in the Taylor Valley, Victoria Land, Antarctica. Tracey Stela, National Science Foundation.

10.2 Climate change over hundreds of millions of years

Continental ice sheets leave behind telltale evidence in the form of scratches and grooves, gouged out by the moving ice, and characteristic deposits containing large boulders moved by the ice. These kinds of evidence in the geological record clearly indicate that major ice ages occurred from about 300 to 260 million years ago (the Late Paleozoic Ice Age) and about 440 million years ago (the Ordovician Ice Age). There is also evidence for the occurrence of a number of extensive earlier ice ages (for example, the Sturtian Glaciation at 710 million years ago and the Marinoan Glaciation at about 640 million years ago). There are also traces of an earlier glaciation roughly 2.3 billion years ago (Figure 10.1). During these Precambrian glaciations, the planet may have been entirely or almost entirely covered by ice. These times have been named Snowball Earth episodes, and are the subject of intense study.

10.2.1 Plate tectonics and continental drift: A cause of major ice ages

For a long time, geologists puzzled over the causes of the long-term oscillations of the global climate between warm intervals and major ice ages. With the acceptance of plate tectonic theory, it became clear that there was a connection between major ice ages and plate movements. The explanation involves a chain of circumstances. During times of very active ocean-floor spreading, new ocean crust is generated at a rapid rate. The new crust is hot and buoyant, causing the Mid-Ocean Ridges to become elevated.[1] This uplift of the ocean floor displaces water from the ocean basins on to the continents, forming shallow

[1] As the ocean lithosphere cools by conductive heat loss, it contracts and its density increases. The increase in density causes the oceanic plate to subside, and hence the depth of the ocean floor increases with its age and distance from the ridge axis. The rate of cooling, rapid at first and then slower, is proportional to the square root of the age of the sea floor. The depth of the ocean floor in relation to its age is given by:

$$\text{Depth} = 2500 \text{ meters} + 350 \sqrt{\text{age}} \text{ (millions of years)},$$

where 2500 meters (7500 feet) is the average ocean depth at the crest of the Mid-Ocean Ridge.

(a)

(b)

FIGURE 10.1 Evidence of past major ice ages.
(a) Glacially scratched and scoured bedrock surface about 430 million years old. This outcrop is located today in the Sahara Desert in Algeria, but 430 million years ago this region was near the South Pole.
R. W. Fairbridge
(b) Glacial deposits from southern Canada dating from about 2.3 billion years ago.
M. R. Rampino

continental seas. Thus, the amount of exposed land area decreases, and the amount of water-covered area increases.

How does the amount of exposed land affect the climate? Land reflects more of the incoming solar radiation back to space than ocean water. Land reflects from 15% for vegetation-covered areas to 35% for bare desert regions. By contrast, ocean water reflects only about 7% of the incoming sunlight back to space, i.e., it absorbs much more of the solar energy than the land does. Thus, the larger the area of Earth's surface covered by water, the more solar energy is absorbed. This tends to warm the planet.

When sea-floor spreading is slow, less of the new warm ocean floor is formed, the ocean floor cools and subsides, and water drains from the continental seas back into the deepening ocean basins. As a result, the amount of dry land increases. This means that more solar energy is reflected, less is absorbed, and the planet is cooled. These conditions are favorable for the onset of a major ice age.

The movement of the continents is another factor in the initiation of major ice ages. When continents drift to polar latitudes, snow and ice can begin to accumulate. The snow and ice reflect an especially large percentage of incoming solar radiation back to space (65% for snow, up to 80% for ice), further cooling Earth, and providing an impetus to further growth of glaciers.

During the most recent or Pleistocene Ice Age (the last 2 million years), there is a concentration of land area in the northern latitudes where the ice sheets wax and wane. During

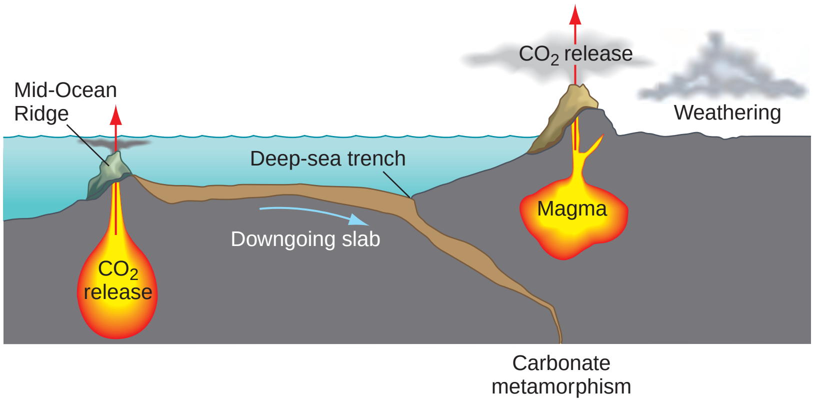


FIGURE 10.2 The carbonate–silicate geochemical cycle. Chemical reactions that weather rock minerals remove carbon dioxide from the atmosphere. This carbon dioxide (CO_2) is eventually locked away as carbonates in ocean sediments. Subduction and heating of these sediments release volcanic carbon dioxide back into the atmosphere, as does volcanism at the Mid-Ocean Ridge.

the Late Paleozoic Ice Age of about 300 million years ago, a large part of the super-continent Pangaea was concentrated near the South Pole, and the Southern Hemisphere land masses were covered by continental glaciers.

The concentration of land at high (polar) latitudes favors the formation and growth of great ice sheets, as noted, reflecting more incoming solar energy, and further cooling the planet. This generates a *positive feedback* effect: formation of ice sheets further cools the planet because ice reflects 80% of solar energy. Cooling of the planet leads to the formation of more ice. Formation of additional ice cools the planet even more, leading to formation of more ice, and so on.

A third important control on long-term climate is the amount of carbon dioxide (CO_2) in the atmosphere. Just as in the Venus atmosphere, carbon dioxide is a greenhouse gas in Earth's atmosphere, though it is only present in traces (about 4 parts of carbon dioxide for every 10 000 parts of air). Through a chain of circumstances, plate tectonics also influences the amount of carbon dioxide in Earth's atmosphere (Figure 10.2). In the first step, carbon dioxide in the atmosphere reacts with surface rocks causing weathering of silicate minerals (through the same chemical reactions discussed in the chapter on Venus). This converts the carbon dioxide to carbonate, e.g., calcium carbonate, $CaCO_3$, and removes it from the atmosphere. (The carbonate is carried in a dissolved form into the ocean, where it is eventually precipitated out as deposits of calcium carbonate (e.g., chalk and limestone), largely in the form of the shells of marine organisms.)

However, the carbon dioxide may be returned to the atmosphere through the processes of plate tectonics. When ocean crust is subducted, the calcium carbonate-rich sediments on the ocean floor are heated, and carbon dioxide is released. Some of this carbon dioxide returns to the atmosphere through subduction-zone volcanoes. The rate at which this recycling of carbon dioxide occurs depends upon several factors. The faster the rate of subduction, which varies with the rate of sea-floor spreading, the faster the recycling of carbon dioxide. The area of the continents exposed to weathering also affects the recycling rate of carbon dioxide, so the greater the area of dry land, the faster the removal of carbon dioxide from the atmosphere by weathering; and the less dry land, the slower the removal of carbon dioxide. This is another reason why low sea level leads to cool temperatures.

The best current estimates of the carbon dioxide content of the atmosphere over the last 600 million years, based on the balance between the supply and removal of atmospheric carbon dioxide are shown in Figure 10.3. These estimates range from today's values to almost 20 times the present carbon dioxide content of the atmosphere.

The amount of carbon dioxide in the atmosphere depends primarily on the rates of plate motion. When sea-floor spreading and hence subduction are fast, volcanism at the Mid-Ocean Ridge releases carbon dioxide, and the chalky

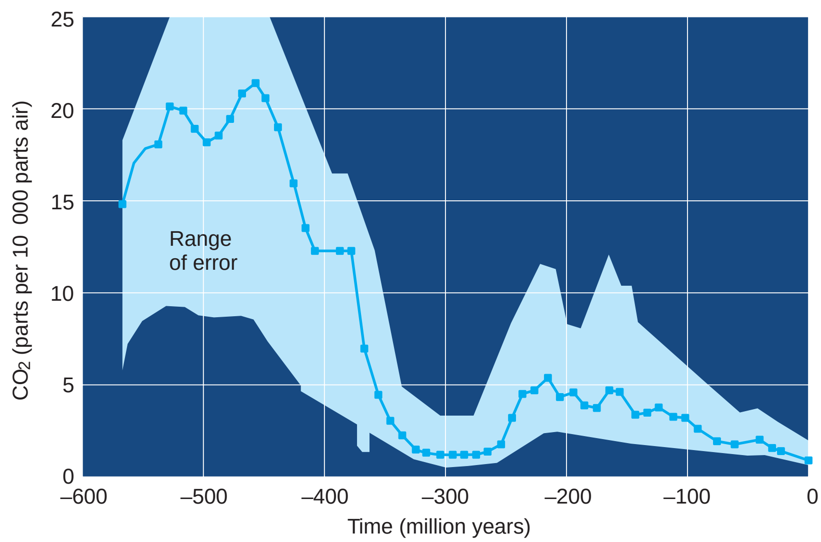


FIGURE 10.3 Carbon dioxide (CO_2) content of the atmosphere for the last 600 million years as estimated from a computer model using geological information on the supply of carbon dioxide to the atmosphere from volcanism and its removal by deposition of calcium carbonate. The range of error is based on geological evidence.

sediments formed in the oceans are rapidly dragged down and heated in the subduction zones, also releasing carbon dioxide to the atmosphere at a greater rate. Since sea level is also high at these times, there is less exposed land, and rock weathering is less efficient in removing atmospheric carbon dioxide, hence the climate remains warm.

Thus, rapid sea-floor spreading creates conditions for a warm climate by enhancing the amount of atmospheric carbon dioxide and the greenhouse effect. This is in addition to the effect of rapid sea-floor spreading in warming the planet by raising sea levels.

When sea-floor spreading is slow, the amount of atmospheric carbon dioxide decreases because subduction of ocean-floor carbonates is slowed. With less carbon dioxide returned to the atmosphere by volcanism, the greenhouse effect is smaller, and the planet is cooled. This cooling effect is in addition to the cooling caused by a drop in sea level, as described above. As global temperature decreases, ice sheets begin to grow, marking the onset of a major ice age.

10.3 Snowball Earth

The most ancient glacial deposits, dating from about 600 million years ago back to more than 2 billion years ago, are widespread, and some are found in regions that were near the Equator at those times in the past. These findings of ice sheets in the tropics suggest that the entire planet, or at least a major portion of it, must have been frozen over. These times of worldwide glaciations or *Snowball Earth* episodes (Figure 10.4) may have been initiated when extensive weathering of continental rocks removed an inordinate amount of carbon dioxide from the atmosphere. As the carbon dioxide levels fell and the climate grew cooler, ice sheets formed and advanced toward lower latitudes, cooling the global climate further by their high reflectivity. The end result was periods of almost total refrigeration of the planet.

The slow buildup of atmospheric carbon dioxide from volcanic eruptions would eventually have warmed the planet sufficiently to melt the global ice cover. After another long

FIGURE 10.4 Deposits from a Snowball Earth episode more than 600 million years ago in Namibia (southwest Africa). This region was near the Equator at that time, suggesting that ice may have covered the entire globe.
Paul Hoffman and Daniel P. Schrag, Harvard University

period during which carbon dioxide was again removed from the atmosphere by rock weathering, Earth would have grown cold enough for ice sheets to reform. These ice sheets again spread rapidly to cover a large portion of the planet. In this way, cycles of global glaciation and deglaciation alternated during each Snowball Earth episode. Many scientists believe that these drastic changes in climate could have created periods of crisis for early life forms. The Snowball Earth episodes ended abruptly about 600 million years ago.

Why have they not recurred? The answer may be that the episodes of planet-wide glaciation were possible early in Earth's history because the early Sun was dimmer and gave off less energy. Astronomers have determined that as the Sun ages it grows brighter. This is because as helium builds up in the Sun's core, the core density increases, and the temperature rises. A hotter core means faster conversion of protons into helium, and thus more energy is released.

10.4 Episodes of climate change lasting tens to hundreds of thousands of years

In the long term, we are now in the midst of a major ice age. Ice sheets formed in Antarctica as early as about 35 million years ago, and during the last 2.5 million years (called the Pleistocene Ice Age) the cooling became so severe that glaciers periodically advanced and retreated across North America and Eurasia. As recently as 18 000 years ago, ice sheets reached their maximum extent and covered most of northern Europe and north America (Figure 10.5).

The temperature record of the last 2.5 million years is shown in Figure 10.6, in which we can see the cooling trend that culminated in the most severe glaciations during the last 500 000 years, accompanied by extreme shifts from cold glacial intervals to warm interglacial epochs.

The climate record of the last 500 000 years shows the progression of cold glacial periods during which ice sheets expand, alternating with warmer interglacial periods in which the ice sheets retreat (Figure 10.7). The succession of glacials and interglacials represents changes of only about 6 °C (about 10 °F) in average global temperature. Note that the warm peaks – times when global temperatures were as high as they are today – make up only a small fraction of the last few hundred thousand years. Note also that none of the interglacial periods of relatively warm, ice-free climate has lasted more than about 10 000 years. The last glacial period ended about 11 000 years ago, so the next glacial epoch would seem to be about 1000 years overdue.

What is the cause of the regular advance and retreat of the ice sheets every 10 000 to 100 000 years within a major ice age? Today, the astronomical explanation put forth by the Serbian mathematician Milutin Milankovitch in the 1920s is generally accepted. Milankovitch suggested that the glacial and interglacial epochs were caused by cyclic variations in Earth's orbit around the Sun, and in the tilt of Earth's axis. These variations affect the amount of solar energy falling on the land areas of the Northern Hemisphere, and especially the distribution of that energy over the seasons.

The perturbations of Earth's orbit are caused primarily by the gravitational pull of the planet Jupiter and Earth's Moon on Earth. Earth's orbit varies in the following ways, as a consequence of these perturbing forces.

The *shape* of Earth's orbit around the Sun changes from circular to elliptical or "egg-shaped" and back every 105 000

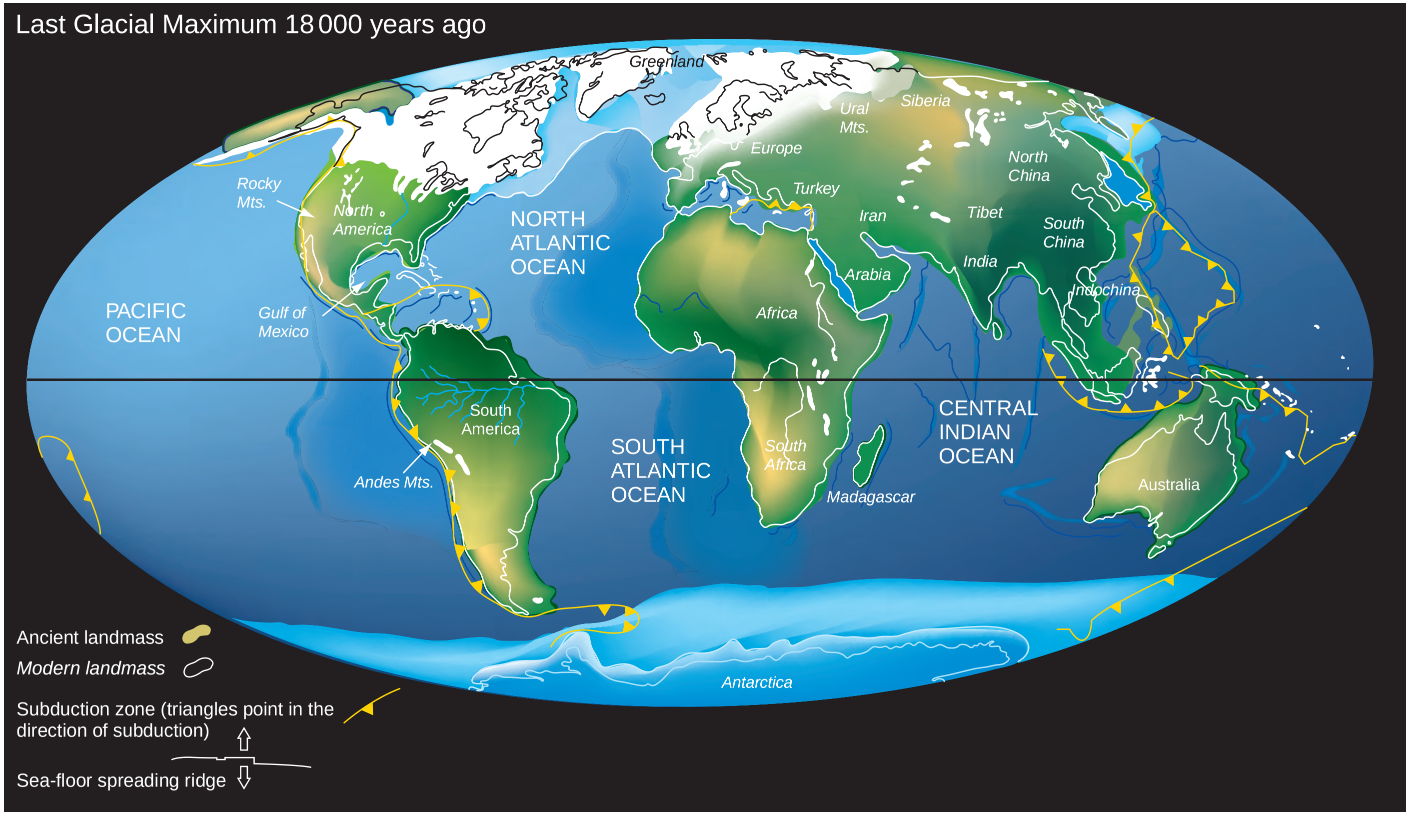


FIGURE 10.5 The last glacial period culminated in ice sheets that covered Northern Europe and North America down to the latitude of New York City about 18 000 years ago.
Christopher R. Scotese

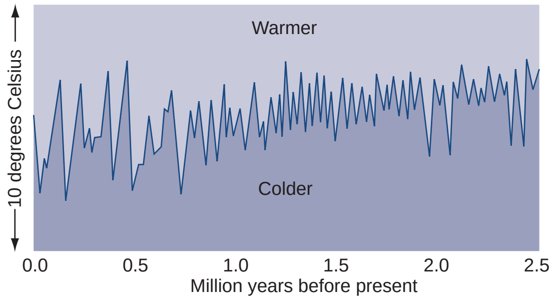


FIGURE 10.6 Fluctuations in global temperatures over the last 2.5 million years. A general cooling trend can be seen, as well as oscillations representing cold glacial and warmer interglacial intervals. Note the increase in the amplitude of the glacial/interglacial swings about 700 000 years ago.

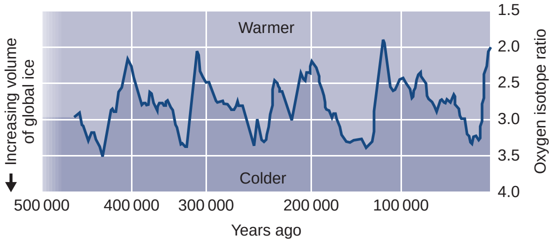
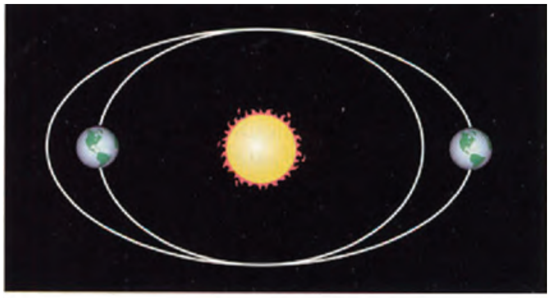


FIGURE 10.7 Glacial and interglacial climate over the last 500 000 years. Glacial periods typically last almost 100 000 years, whereas interglacials last only about 10 000 years.

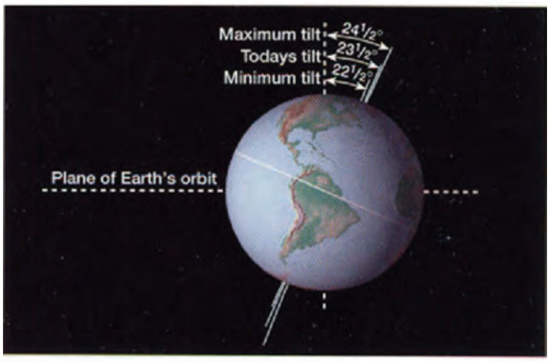
years (Figure 10.8(a)). In the most extreme case, however, the egg-shape is only about 10% from circular. At the present time, the orbit is about 2% from circular, and is becoming even more circular.

Earth's axis of rotation precesses every 23 000 years, i.e., Earth wobbles like a top, taking 23 000 years to complete one wobble (Figure 10.8(b)). This effect is mainly caused by the Moon's gravitational pull. The precession of Earth's axis affects the direction in space in which Earth is tilted at any time of the year. Today Earth's axis points almost exactly to the star Polaris. Five thousand years ago it pointed to the star Thuban, and 11 500 years from now the axis will be pointing at Vega. The effect of precession is to reverse the hemisphere experiencing summer at the time of closest approach of Earth to the Sun. Today, Earth is closest to the Sun in January, but 11 500 years ago Earth was closest to the Sun in July, corresponding to Northern Hemisphere summer.

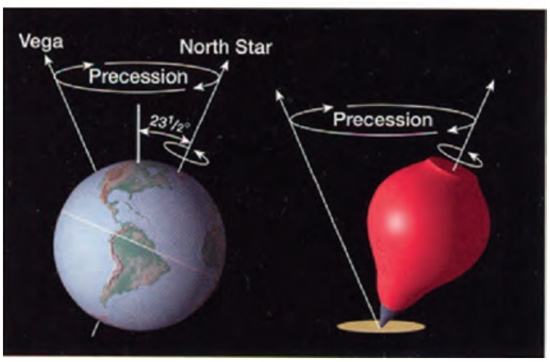
The angle of *tilt* of Earth's axis also changes, from about 22.5° to 24.5° and back again every 41 000 years (Figure 10.8 (c)). The present angle of tilt of the axis is 23.5°, and this angle is currently decreasing. The smaller the angle, the smaller the temperature difference between the seasons. Hence, winters are milder and summers cooler.



(a)



(b)



(c)

FIGURE 10.8 Changes in Earth's orbit.
(a) Earth's orbit changes shape from egg-shaped (ellipse) to circular every 105 000 years (not to scale).
(b)Tilt changes from 22.5° to 24.5° every 41 000 years.
(c) Precession of Earth's axis of rotation every 23 000 years, in which Earth acts like a wobbling top.

Terbuck, E. J. & Lutgens, F. K., *Earth Science*, 9th,

These circumstances change the intensity of solar radiation striking the land areas in the Northern Hemisphere during the various seasons, and therefore change the rate of snow and ice accumulation on the northern continents. To see why this is so, consider the present situation on Earth. At the present time, because of the somewhat elliptical shape of Earth's orbit, Earth's distance from the Sun varies by 3 million miles during the course of a year. In what part of the year is Earth closest to the Sun? At present this occurs in the month of January, when the Northern Hemisphere is tilted away from the Sun (Figure 10.9).

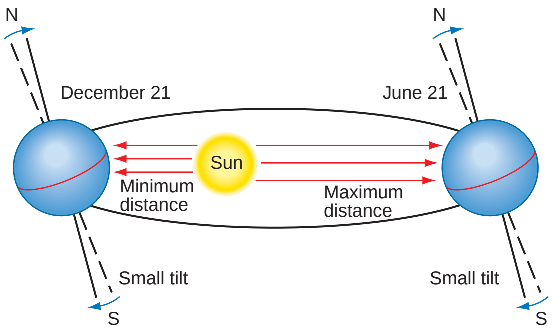


FIGURE 10.9 Conditions for mild winters and cool summers in the Northern Hemisphere (reduced seasonal variation). (Left) Earth's axis is tilted *away* from the Sun in the Northern Hemisphere when Earth is closest to the Sun in its orbit. (Right) axis is tilted toward the Sun when Earth is farthest from the Sun in its orbit. Mild seasonality and glaciation begins. This is the situation now. We are headed into a glacial period. (Not to scale. The actual difference in winter/summer distance from the Sun is about 3%.)

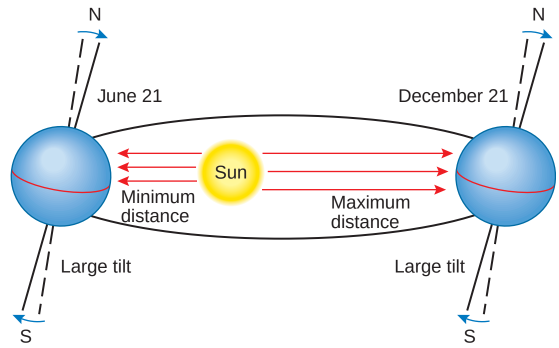


FIGURE 10.10 Conditions for cold winters and hot summers in the Northern Hemisphere (extreme seasonal variation). (Left) Earth's axis is tilted *toward* the Sun in the Northern Hemisphere when Earth is closest to Sun in its orbit. (Right) axis is tilted *away* from the Sun in the Northern Hemisphere when Earth is farthest from the Sun. During times of extreme seasonality, ice sheets melt, leading to an interglacial period. (Not to scale. The actual difference in winter/summer distance from the Sun is about 3%.)

Because the Northern Hemisphere is tilted away from the Sun, the Sun's rays are incident on the Northern Hemisphere at an oblique angle, and we receive less solar heat. That is why the winter season prevails in the Northern Hemisphere (remember, in Australia, January is mid-summer). However, because the Earth is relatively close to the Sun at that time, the Northern Hemisphere winters tend to be relatively mild. At the same time, the summers in the Northern Hemisphere tend to be relatively cool.

Now consider the situation roughly 11 500 years in the future (one-half the precession cycle), when, because of the precession of Earth's axis, the tilt of the axis is in the opposite direction in space. Now the Northern Hemisphere is tilted *toward* the Sun, and therefore experiencing summer, at just the time when Earth is closest to the Sun (Figure 10.10). Therefore, Northern Hemisphere summers should be relatively hot. Six months later, on the other side of Earth's orbit, the Northern Hemisphere is tilted away from the Sun (winter) just when Earth is farthest from the Sun. Therefore, the winters should be quite cold.

Present conditions on Earth are such as to make for a succession of mild winters and cool summers. Eleven thousand years from now, conditions will be such as to produce a succession of cold winters and hot summers in the Northern Hemisphere.

The effects we have just described depend on how egg-shaped (elliptical) the orbit is. These effects are greatest when the orbit is very egg-shaped and the Sun–Earth distance is accordingly very different in January than in June. The effects also depend on the tilt of the axis. When the tilt of the axis is at its greatest value of 24.5°, the effects are enhanced, but they are diminished when the tilt is less. (If the tilt were zero, i.e., Earth's axis were always exactly perpendicular to the plane of its orbit, there would be essentially no seasons on our planet.)

How do these variations in Earth's orbit lead to the alternate growth and retreat of ice sheets? When the orbit is such that Northern Hemisphere winters are extremely cold, as in Figure 10.10, it would seem that snow and ice accumulation should be most rapid, i.e., a glacial period should result. However, the data show the opposite: The ice starts to accumulate during the periods in which the Northern Hemisphere winters are relatively mild and the summers are cool as in Figure 10.9.

Heavy snow will occur in most winters, but cool summers mean that the winter snow that falls is more likely to last through the summer, accumulating from year to year to become permanent snowfields. The snowfields are converted to ice sheets by the pressure of the accumulating snow, and eventually the thick ice flows outward to form continental glaciers.

The growth of the ice sheets actually speeds up the cooling of the planet. Ice, being white, reflects most of the incident solar energy back to space, whereas water and land absorb most of this energy. The presence of snow and ice cover, therefore, means that Earth is absorbing less energy from the Sun. This effect leads to further growth of the ice sheets;

when the ice sheets become larger, Earth absorbs still less solar heat; and so on. For this reason, the ice sheets increase in size very rapidly once they start to grow, until they cover a considerable portion of the land area of Earth.

Another process that amplifies the global cooling involves atmospheric carbon dioxide and methane. We know from analyses of air bubbles trapped inside ancient layers of polar ice that during glacial periods the atmospheric carbon dioxide and methane content were lower than during interglacials. This reduction in greenhouse gases would cause a further cooling of the climate during the glacial periods.

Is there any evidence that this explanation of the ice ages is correct? In the mid 1970s, a group of researchers found that the record of glacial and interglacial periods in the last 500 000 years (as shown in Figure 10.8) could be broken down into cycles with clear periods of 23 000, 41 000, and 100 000 years. These periods agree so well with the cycles of changes in Earth's orbit listed above as to leave little doubt that the two phenomena – the orbital changes and the glacial/interglacial cycles – are related.

10.5 Short-term climate change: The last 10 000 years

We emerged from the last glacial period about 11 000 years ago. Our climate since that time has been marked by relatively small changes of 0.5 to 2 °C (about 1 to 4 °F) in global temperature (Figure 10.11). However, these seemingly small changes in climate have had significant effects on human activities.

The warming in the present interglacial reached a peak about 6000 years ago, in about 4000 BC. This period of mild climate may have led to large agricultural yields and food surpluses. It has been suggested that the birth of civilization in Mesopotamia and Egypt was made possible by the new surpluses of food, which allowed new members of society such as administrators, teachers, and lawyers to exist in appreciable numbers for the first time.

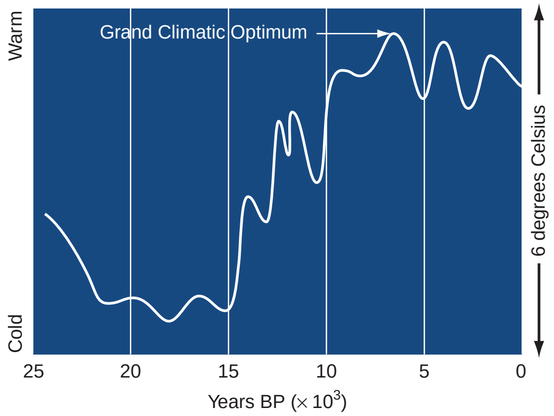


FIGURE 10.11 The last 25 000 years of climate, including the present interglacial, showing broad climate trends, notably the Grand Climatic Optimum of about 6000 years ago. That was the warmest time within the present interglacial. Twentieth century climate is shown in Figure 10.12.

This so-called *Grand Climatic Optimum* of about 4000 BC. was followed by a general cooling trend. Another period of pronounced climate change occurred between AD 800 and AD 1300, when Earth experienced a warming that has been called the *Medieval Warm Period*. During that period, Northern Hemisphere temperatures increased by a few tenths of a degree Celsius. However, that small change had far-reaching effects, for the period of moderately warm weather expanded the growing season and the amount of arable land in the Scandinavian countries. The population in these countries expanded accordingly, and the Vikings began to push east, south, and west. They captured Paris in AD 845, and reached the area of Moscow in the same period.

10.5.1 The Medieval Warm Period

In their drive to the west, the Vikings sailed across the North Atlantic and settled in Iceland, Greenland, and North America (Newfoundland, named Vinland by the Norse because they found grapes growing there) around AD 1000. The Vikings were able to accomplish this because the North Atlantic was relatively calm and free of sea ice during the Medieval Warm Period. The Norse also set up colonies in coastal Greenland and raised crops in an area that today is a frozen ice-covered waste. But in the fourteenth century, as the climate worsened, the North Atlantic colonies were cut off from their homeland by sea ice and increasing storminess. As the cold weather closed in, the Greenland colony became extinct by about AD 1400, leaving America to be rediscovered by Columbus.

10.5.2 The Little Ice Age

A cooling trend is recorded from the fifteenth to the late nineteenth centuries as the world sank into the *Little Ice Age*. Average temperatures in the Northern Hemisphere dropped by only a few tenths of a degree Celsius, but average winter temperatures decreased as much as 20 °C (about 40 °F). These small changes led to a shortened growing season and contributed to severe famines and social unrest in Europe. In the late 1500s, for example, several million people in France and neighboring countries starved to death in climate-related famines.

Historical records reveal that the winters of the time were extremely severe. For example, snowfall in Europe was quite heavy, spring thaws were late, and major rivers were frozen over all winter. Popular frost fairs were held each year on the thick ice cover of the River Thames in England. In recent times, the Thames remains ice-free all winter long.

Temperatures began to rise in the 1700s, dropped somewhat around the beginning of the nineteenth century, and stayed rather cool for much of the 1800s. Figure 10.12 shows the global climate of the last 120 years. This record represents a compilation of data from many weather stations around the globe.

Large year-to-year variations in temperature of up to 0.5 °C (about 1 °F) are evident on the graph, and these year-to-year

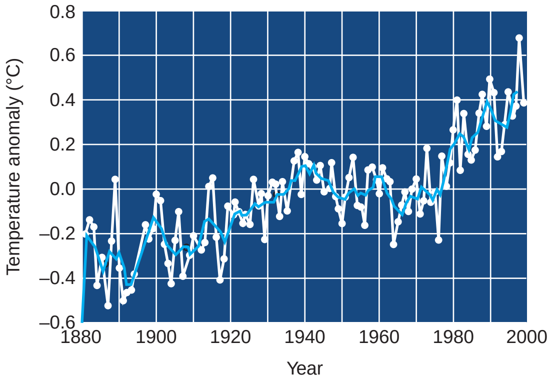


FIGURE 10.12 Average yearly global temperatures from AD 1880 to 2003 compiled by climatologists at NASA's Goddard Institute for Space Studies. The white line represents the year-to-year variations, and the blue line is the 5-year mean that shows the longer-term trends. NASA

FIGURE 10.13 The Argentière glacier in the French Alps. (a) An etching made about 1850 showing the extent of the glacier during the Little Ice Age. (b) The same view photographed in 1966. The glacier retreated drastically up the valley in the twentieth century.

variations can obscure trends in climate. To overcome this problem of a noisy year-to-year record, we can look at five-year averages (shown by the solid line in Figure 10.12) over the entire period of observation. The average reveals several distinct climate trends: A general warming from the late 1800s to the 1940s, a slight cooling trend from the 1940s into the 1970s, and a warming trend from the late 1970s to the present. The long-term climate trend for the entire twentieth century was a net warming of about 0.8 °C (about 1.5 °F).

The increase in global temperature in the last 100 years has been accompanied by indications of climatic warming such as an earlier spring thaw, increase in the number of very hot summers, and the retreat of many of the world's mountain glaciers (Figure 10.13).

10.6 Causes of short-term climate change

10.6.1 Volcanic eruptions and climate

What are the causes of changes in climate that last from a few decades to a few hundred years? Several factors are believed to be important. Volcanic eruptions emit copious amounts of the gas sulfur dioxide (SO_2), which is converted to droplets of sulfuric acid (H_2SO_4) in the upper atmosphere (Figure 10.14). The sulfuric acid droplets (or *aerosols*) create a global haze that shields Earth's surface from the Sun, and cools the planet.

The global cooling caused by large explosive eruptions can be substantial, of the order of several tenths of a degree

FIGURE 10.14 The explosive eruption of Mount Pinatubo in the Philippines in 1991. This sulfur-rich volcanic eruption created a global veil of sulfuric acid aerosols in the upper atmosphere.
NOAA National Geophysical Data Center

Celsius. Several volcanic eruptions in historic times have been accompanied by noticeable decreases in temperature – for example, Tambora in Indonesia, in 1815, was followed by unusually cool weather, crop failure, and widespread famine in Europe and North America in 1816, the so-called "year without a summer." The Indonesian eruptions of Krakatau in 1883 and Mount Agung in 1963 also led to a few years of global cooling. Most recently, the eruption of Mount Pinatubo in the Philippines in 1991 produced the densest aerosol haze in 100 years, which enveloped the globe and cooled global climate by a few tenths of a degree Celsius in 1992 and 1993. However, the particles that cause the cooling disappear from the atmosphere in a few years, so that the climatic effects of even the largest eruptions are relatively brief.

10.6.2 Climate and the Sun's brightness

Changes in the Sun's brightness are another possible contributor to short-term climate change. One indication of solar activity is the presence of dark spots on the Sun's surface. *Sunspots*, first observed in modern times by Galileo in 1609, are regions of the Sun that are a few thousand degrees cooler than the gas surrounding them (about 4000 °C, compared to 6000 °C for the surface of the Sun as a whole) so they look dark compared to the areas around them. The spots commonly appear on the Sun in pairs, aligned in an approximately east–west direction.

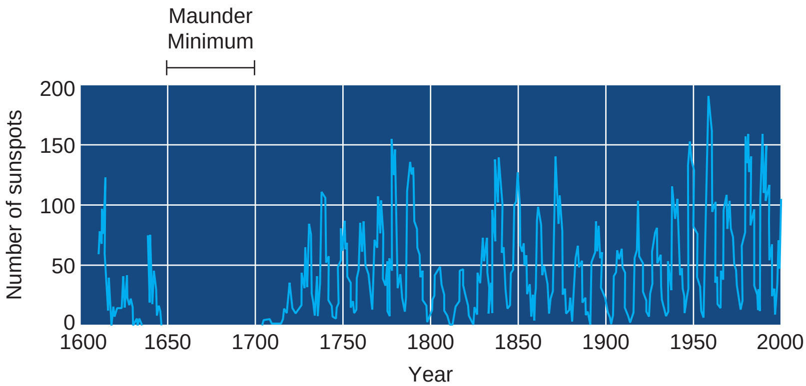


FIGURE 10.15 Numbers of sunspots AD 1600 to 2000 showing an 11-year cycle, and longer envelope of sunspot maxima. The period from about AD 1650 to 1710 – called the Maunder Minimum – was marked by a complete absence of observable sunspot activity, which correlates with the most severe part of the Little Ice Age.

Sunspots are caused by disturbances in the magnetic field of the Sun, which are caused in turn by the Sun's rapid rotation (the Sun rotates once every 27 days). They are accompanied by other solar disturbances such as *solar flares* – violent outbursts of energy and particles – and *solar prominences* – huge loops of luminous gases that erupt from the Sun and rise hundreds of thousands of miles above the solar surface.

Sunspots show an 11-year cycle of increases and decreases in the numbers of spots (Figure 10.15). Measurements of solar radiation using sensitive instruments on satellites have confirmed changes of about 0.1% in the Sun's output over the sunspot cycle. Scientists have discovered 11-year cycles in climate records such as growth rings in trees, which suggests that even small fluctuations in solar activity can affect climate. But the clearest connection between sunspots and climate has turned out to be somewhat different than originally expected. Note that the numbers of sunspots per cycle shown in Figure 10.15 are variable, changing roughly every hundred years in a fairly regular way. Furthermore, the length of a sunspot cycle, which averages 11 years, actually varies between about 9 and 15 years. Calculations by climatologists show that a small change in solar energy output could have led to the changes in climate seen in Europe during the Little Ice Age.

John Eddy at the US National Center for Atmospheric Research assembled evidence indicating that from about AD 1650 to 1710 there was almost no sunspot activity. This *Maunder Minimum* (named after an early twentieth-century astronomer who argued for its existence) coincides with the depths of the Little Ice Age. The cool temperatures in the early nineteenth century also correspond to a very low number of spots in that period.

According to Eddy, the coincidence between the Maunder Minimum and the Little Ice Age provides a clue to the cause of such century-long climate changes. It is *not* that sunspots themselves cause the climate change, but rather that the Sun's energy output is changing on a 100-year timescale, and the variations in solar energy and sunspots are both manifestations of some fundamental process going on deep within the Sun.

10.6.3 Carbon dioxide and climate: The human factor

Earth's greenhouse effect, primarily a result of carbon dioxide and water vapor in the atmosphere, keeps the surface temperature of the planet about 15 °C (27 °F) warmer than it would be without these gases. The amount of carbon dioxide and other greenhouse gases in the atmosphere has been rising over the past few centuries as a result of human activities.

The amount of carbon dioxide in the atmosphere has increased by about 40% over pre-industrial levels (Figure 10.16). Added to the increased carbon dioxide are increases in other greenhouse gases, such as methane (CH_4) from agricultural practices, nitrous oxide from nitrogen-based fertilizers, and chlorofluorocarbons (CFCs) from refrigeration and other industrial uses. Many scientists believe that a major part of the twentieth century warming has been caused by this increase in atmospheric carbon dioxide and other greenhouse gases.

What does the future hold in store? If we continue to burn coal and oil at present and projected rates, an amount of greenhouse gases equivalent to a 100% increase in carbon dioxide

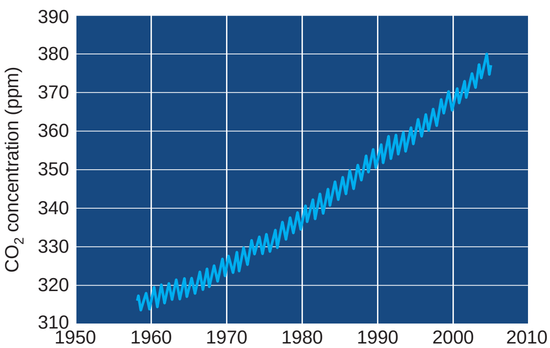


FIGURE 10.16 Observed increase in atmospheric carbon dioxide from 1957, when these measurements began, to 2005. The pre-industrial atmospheric carbon dioxide, as determined from air bubbles trapped in polar ice, was only 285 parts per million. Note the increasing trend, and the seasonal cycle that is controlled by the growth and decay of Northern Hemisphere vegetation each year. NASA

over pre-industrial values may exist in the atmosphere by the middle of the twenty-first century. Calculations suggest that this increase in carbon dioxide could cause a warming of the planet that would put stress on natural ecosystems and agriculture, increase the frequency and intensity of tropical storms, and lead to many other climatic and ecological changes.

Recently, representatives of the various nations have been meeting to try to reach agreements on limiting CO_2 emissions from fossil fuel burning in an attempt to slow global warming. Increased energy efficiency, alternative energy sources, and possible capture and sequestering of carbon dioxide emissions, along with reductions in release of other greenhouse gases would slow or reduce future global warming.

The amount of carbon dioxide in Earth's atmosphere has varied over geological time. The changing greenhouse effect and other factors have caused pressures on the forms of life, and have provided a major driving force for the evolution of life on Earth.

10.7 Summary

By the end of this chapter you should be familiar with the following concepts and topics:

Fluctuations of Earth's climate
Timescales of climate change
The occurrence of major ice ages
  Their connection to plate movements
  Changes to the surface of Earth
The causes of climate changes within each major ice age
  Cause of a regular advance and retreat of the ice sheets
  Linkage with Earth's orbit around the Sun
Short-term climate change and its effects on human activities
  Natural causes of short-term climate change: volcanic eruptions and the Sun's brightness
  Human-related causes of short-term climate change: carbon dioxide
What is in store for us in the future?

Questions

10.1. Describe three kinds of changes in Earth's orbit during the last 300 000 years.
10.2. How do these changes affect global climate?
10.3. Explain the relationship between volcanic eruptions and climate.
10.4. What is the effect of changes in the relative amounts of land and sea through time on the climate?
10.5. What are the predicted effects of fossil-fuel burning on the atmosphere and climate?