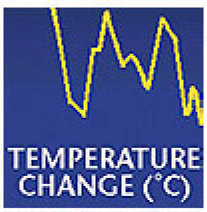
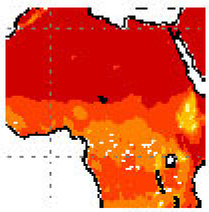
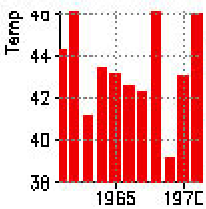
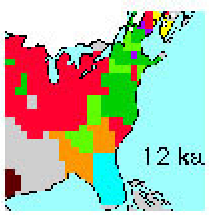
Earth's Climate System





Climate . . . is fundamental by reason of its vital influence upon the quantity and quality not only of man's food but of most of his other resources; . . . and through its effect upon human occupations, modes of life, and habits, it is one of the main determinants of culture.

Ellsworth Huntington

What has happened, can happen; climatic history can repeat itself.

Reid Bryson

Introduction

- Weather is the state of the atmosphere at a given time and place.
- Climate represents average weather conditions for a place over a long time period (years).

Weather represents the state of the atmosphere at a given time and place. Characterizing weather requires that we measure conditions such as temperature, precipitation, air pressure, wind speed and direction, humidity. In contrast, **climate** is the average weather conditions for a site measured over a long time period (years). We must review weather data for several decades to thoroughly characterize a region's climate (Figs. 1, 2).

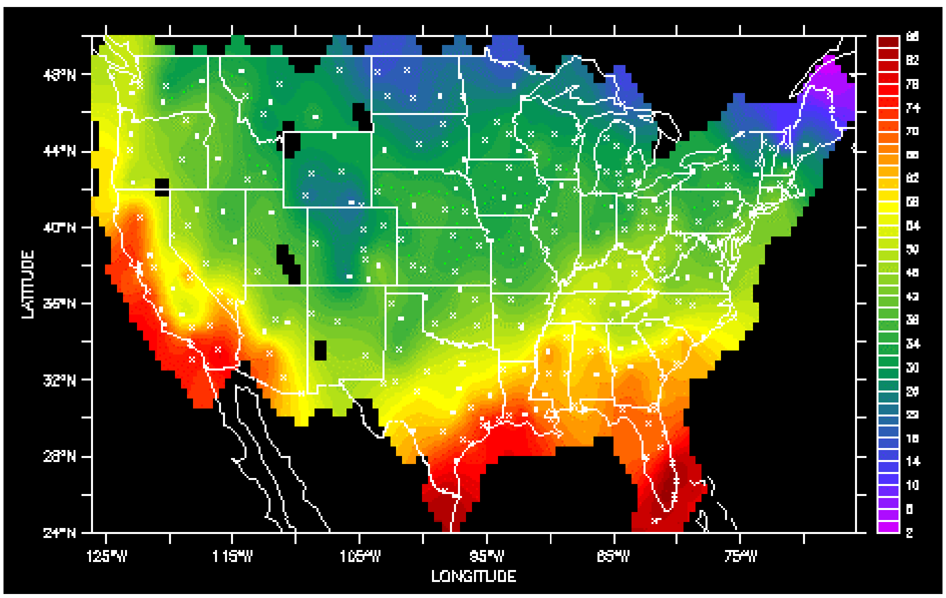
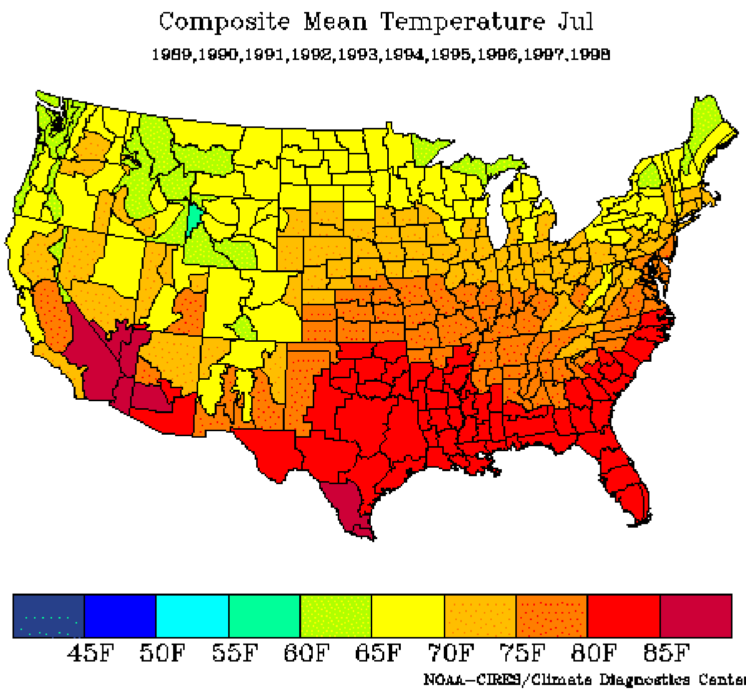


Figure 1. Maximum temperatures across the continental U.S. on January 1, 1996. High temperatures ranged from the high 80s (Florida) to freezing (northern Maine). The daily temperatures represent weather conditions but the overall temperature distribution (cold in the north, warm in the south) reflects regional climate patterns. Image courtesy of the National Climatic Data Center.

Weather and climate are the result of a complex series of interactions between all elements of the Earth system (hydrosphere, atmosphere, biosphere, solid Earth) but are largely controlled by the interaction between the Earth and Sun. The distribution of **solar radiation** on the Earth's surface regulates the length and order of the seasons. The tilt of Earth's axis results in North America receiving more solar radiation in summer and less in winter. (See the Earth & Sun section of the chapter, Earth in Space, for more on natural variations in the distribution of solar radiation.)

Solar radiation strikes the earth more directly at the equator and tropics than in polar regions. More heat is therefore transferred to Earth in the tropics than at the poles. **Global atmospheric circulation patterns** represent the planet's attempt to move warm air toward the poles and cold air toward the equatorial region. These patterns are complicated by Earth's rotation, dividing into three large convection cells in the Northern and Southern Hemispheres that control climate patterns. **Global temperature and precipitation** patterns are directly related to



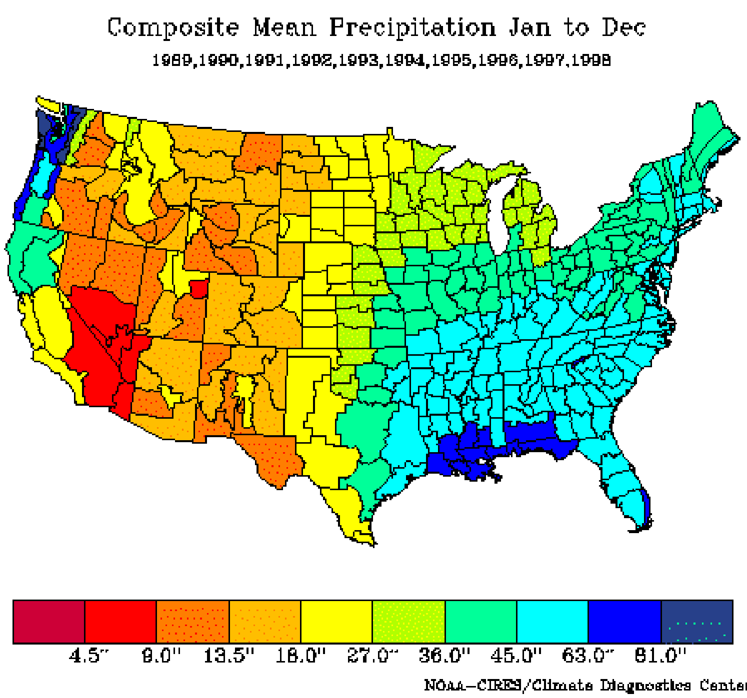


Figure 2. Top: Mean temperature in the continental U.S. for the month of July. Highest temperatures are in the Southwest, lowest temperatures in the Northwest and Northeast. Bottom: Mean annual precipitation for the continental U.S. Precipitation is greatest in southeastern and northwestern states and is least in the Southwest. Images courtesy of NOAA.

global atmospheric circulation patterns and differentiate climate regions across the globe.

Areas with consistent climates are grouped together in **climate regions**. Climate regions are differentiated on the basis of monthly temperatures, monthly precipitation, and precipitation values (Fig. 2). Archeological, historical and geologic records indicate that Earth has a complex, changing **climate history**. These **climate records** give indirect evidence of past climate change over both the long-term (millions of years) and short-term (hundreds or thousands of years).

The cause of long-term global climate changes (**causes of climate change**) are processes that operate over intervals measured in millions of years. The most likely causes are associated with the changing locations of continents and oceans (plate tectonics) that in turn affect atmospheric and oceanic circulation patterns. Short-term climate fluctuations occur on cycles lasting thousands of years and are related to variations in Earth's orbit around the Sun that cause the amount of insolation (incoming solar radiation) to vary with time.

Think about it . . .
What spatial and temporal variations in global climate patterns must a global climate model be able to explain?

Global Air Circulation

- Insolation, incoming solar radiation, is greatest at the equator and least at the poles.
- Global atmospheric circulation transfers heat from the equator toward the poles.
- Airflow on a non-rotating earth would generate one convection cell per hemisphere.
- The Coriolis effect causes atmospheric circulation to be divided into three cells per hemisphere (Hadley, Ferrel, Polar cells).

- Global cloud patterns are linked to the distribution of low- and high-pressure systems that separate the convection cells

Solar radiation strikes Earth more directly at the equator and tropics than in polar regions. Radiation strikes Earth at a lower angle near the poles and the Sun's rays must therefore penetrate a greater thickness of atmosphere. Some of the solar radiation is **scattered** in the atmosphere and heat energy is lost near the poles as a result of scattering. Furthermore, the same amount of heat energy is distributed over a **larger area** near the poles than at the equator. Consequently, the atmosphere above **the equator receives 2.5 times more insolation**, incoming solar radiation, than the atmosphere above the poles. More heat is therefore transferred to Earth in the tropics than at the poles. Contrast in insolation at the poles and equator creates a **heat gradient** that causes warm air to be transferred toward the poles. Global air circulation patterns represent the planet's attempt to move warm air toward the poles and cold air toward the equatorial region.

A Non-Rotating Earth

Global atmospheric circulation patterns would be simple if Earth did not rotate. Warm air would rise at the equator, forming one limb of a hemisphere-scale convection cell that would carry cold dense air to the tropics and warm, less dense air to the poles (Fig. 3). Airflow in this idealized world would be driven by pressure differences between the equator and poles and would be meridional (parallel to longitude, north-south).

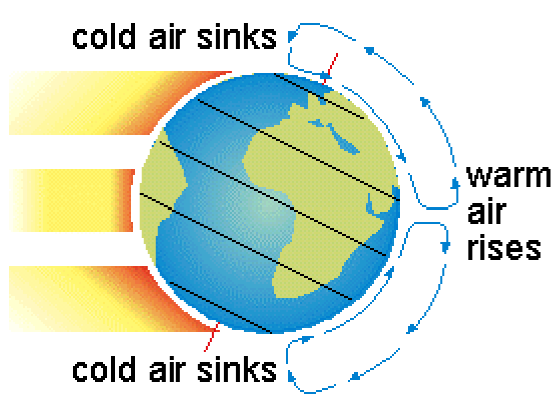


Figure 3. Simple global circulation model that would occur on a non-rotating Earth. This model would be complicated by variations in the distribution of land and oceans.

Rotating Earth

Of course Earth does rotate once on its axis each day and the resulting **Coriolis effect** causes the meridional flow to be disrupted as winds are deflected to the right of their course in the Northern Hemisphere and to the left of their course in the Southern Hemisphere. Atmospheric circulation can be divided into three convection cells in each hemisphere. From equator to the poles these cells are the **Hadley cell**, **Ferrel cell**, and **Polar cell** (Fig. 4).

Hadley Cell: Warm air converges on the equator and rises, forming a belt of low pressure (Fig. 4; **equatorial low**). The humidity of the air increases as it cools during its ascent causing condensation and cloud formation. Precipitation follows as temperatures continue to decline with elevation; consequently, equatorial regions are characterized by ecosystems dependent upon heavy rainfall (e.g., tropical jungles). This air then moves north or south toward the tropics.

A high-pressure zone, a **subtropical high**, of descending air is present between 20-35 degrees latitude in the Northern and Southern Hemispheres (Fig. 4). The descending air becomes warmer and its relative humidity decreases as elevation decreases, preventing condensation and resulting in clear skies over the tropics. Most of the descending air flows toward the

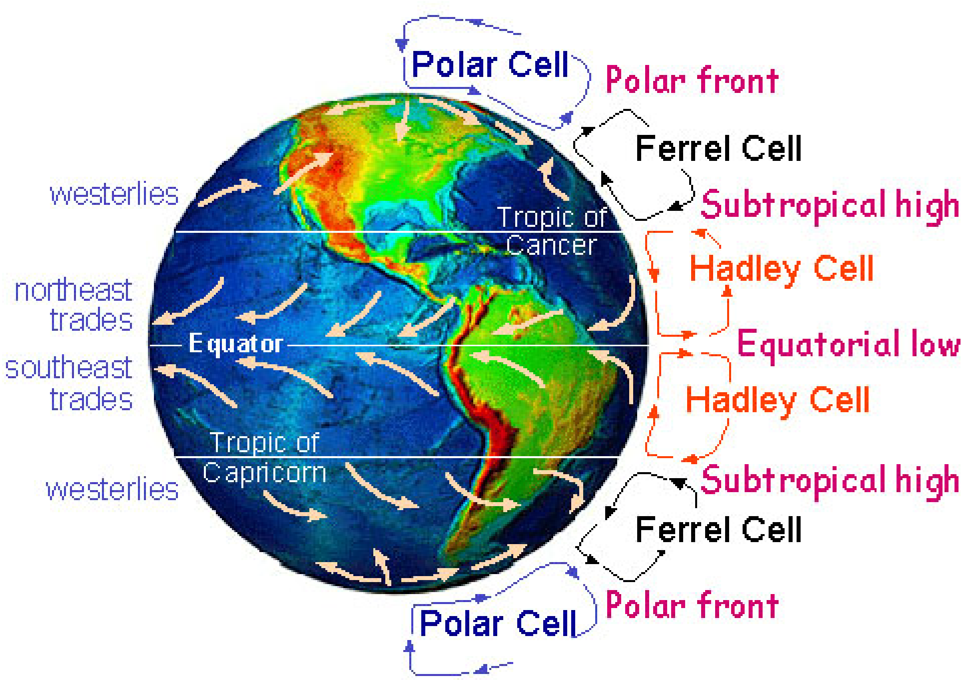


Figure 4. A model of atmospheric circulation showing the convection cells in each hemisphere and the low- and high-pressure systems and wind patterns that result from their interaction. The Sun is assumed to be overhead at the equator. Earth has been rotated to better illustrate the distribution of circulation cells.

equator, forming the last leg in a convection cell. These winds are deflected to the west in the Northern Hemisphere and to the east in the Southern Hemisphere creating the **trade winds** (northeast trades, southwest trades).

Ferrel cells: Mid-latitude cells in both hemispheres are termed the Ferrel cells (Fig. 4). Circulation in these cells results from the air flowing toward the poles from the subtropical highs which collides with cold air flowing from the poles. The zone of convergence is the **polar front**, a zone of high pressure characterized by ascending air and cloud formation.

Polar Cells: Cold, dense air descends in a polar high-pressure system and moves toward the equator (Fig. 4). The polar front is a zone of convergence where the surface winds from the Ferrel and Polar cells meet.

Bands of clouds form where condensation takes place above the rising, cooling air at the equatorial low and the polar fronts (Fig. 5). In contrast the skies are relatively clear over areas of descending, warming air such as the subtropical highs and the poles (Fig. 5). The global distribution of temperature and precipitation is directly related to variations in incoming solar radiation and the atmospheric circulation patterns described above.

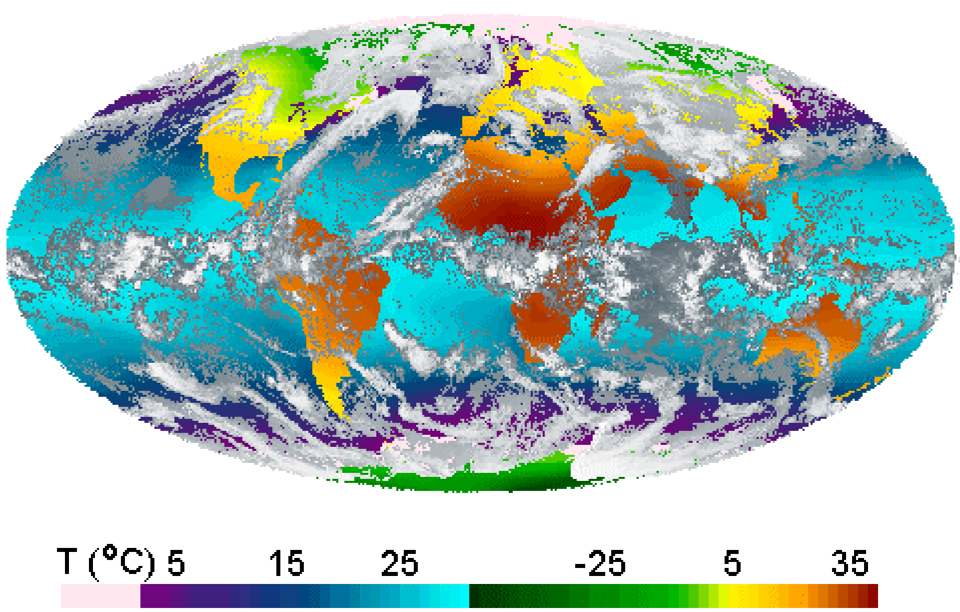


Figure 5. Global cloud cover, sea surface temperatures and land surface temperatures for March 24, 1998. Note the cloud cover over the equator (equatorial low) and clear skies over the tropics (subtropical high). Image courtesy of the Space Science and Engineering Center at the University of Wisconsin, Madison.

Think about it . . .
How would the bands of clouds and clear skies associated with the equatorial low and subtropical highs alter position on Earth with the changing seasons?

Global Temperature and Precipitation

- Temperatures are greatest in equatorial regions and decrease toward the poles.
- Precipitation is greatest above the equatorial low-pressure system.
- Precipitation is least above the subtropical high-pressure systems.

Temperature

Temperatures are greatest in the equatorial regions and decrease toward the poles. This is a direct result of the fact that more heat energy is absorbed at the equator than the poles. The **mixing of ocean currents** results in less extreme temperatures in oceans adjacent to land masses (Fig. 5). High temperatures in the deserts of North Africa are not matched in the relatively narrow isthmus of land that makes up Central America where temperatures are moderated by the Pacific Ocean to the west and Gulf of Mexico to the east. Likewise, the bone-chilling sub-zero cold of the Antarctic interior is not matched in the waters of the Southern Ocean where temperatures remain a few degrees above freezing (Fig. 5).

The world's highest temperature 58^{o}C (136^{o}F) was recorded in the desert of El Azizia, Libya, North Africa (Fig. 6). The highest temperature in North America was a few degrees less (57^{o}C, 134^{o}F) and was recorded in Death Valley, California. The lowest temperature ever recorded was registered at Vostok station, Antarctica at -89^{o}C (-129^{o}F). The lowest North American temperature recorded was -63^{o}C (-81^{o}F) at Snag, Yukon, Canada.

Precipitation

Spatial variations in precipitation are related to variations in temperature and the **global atmospheric circulation** system.

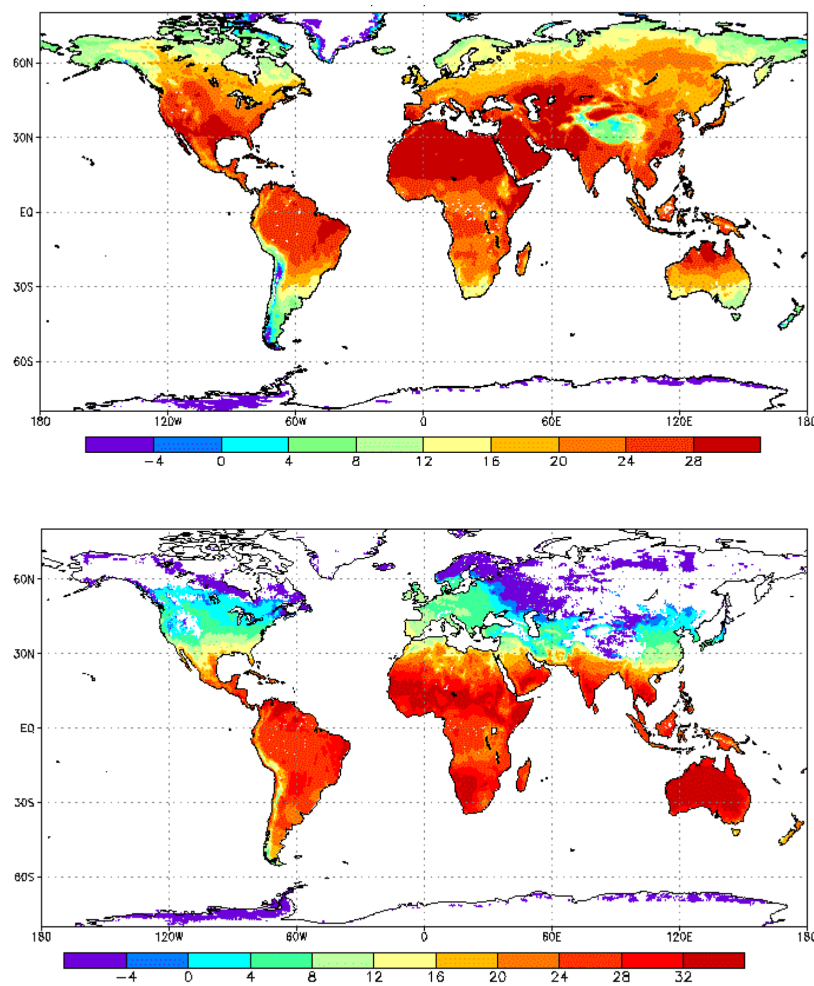


Figure 6. Top: Average global temperatures in degrees Celsius for August 1998. Bottom: Average global temperatures in degrees Celsius for February 1998. Image courtesy of NCDC SSMI satellite website.

Precipitation is greatest where ascending moist air becomes saturated as it rises and cools. Air rises in zones of low pressure above the equatorial low and the polar front. The warmest air and greatest evaporation rates are associated with the **equatorial low**. Consequently, precipitation is greatest near the equator (Fig. 7). The high temperatures and abundance of precipitation that characterize this region support life in the tropical rain forests. The world's highest average annual precipitation was estimated as 1,310 centimeters (over 43 feet or 524 inches of rain) at Lloro, Colombia, in equatorial South America.

Precipitation is least in regions where **descending dry air** becomes warmer, increasing its potential to absorb moisture. Air descends in the subtropical highs centered between 20 to 35 degrees North and South (Figs. 7, 8). These areas are home to the world's major **deserts** (Sahara, North Africa; Gobi,

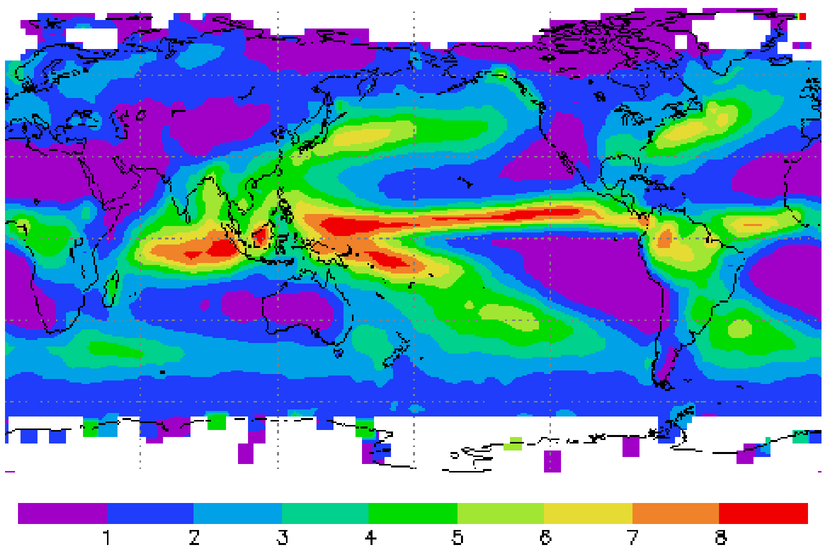


Figure 7. Average global precipitation in millimeters per day (1988-1996). Greatest precipitation is concentrated over the equatorial region; least precipitation is over subtropical regions. Image courtesy of the Global Precipitation Climatology Project.

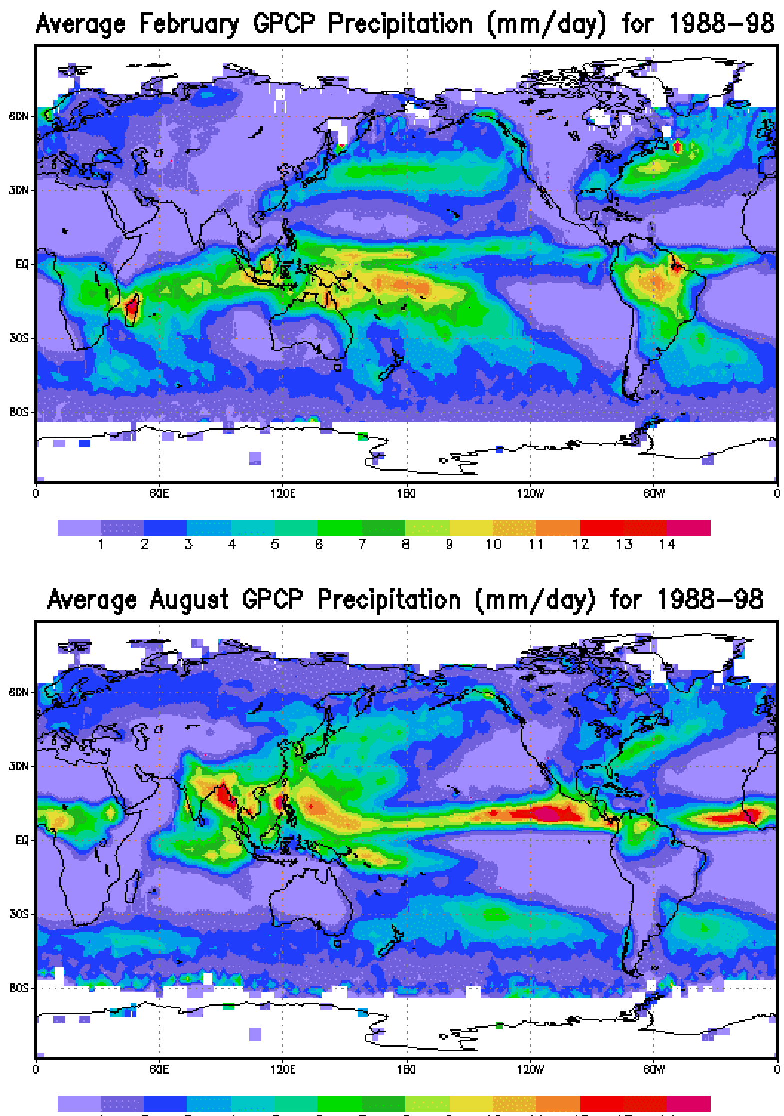


Figure 8. Average monthly precipitation over a 10-year period (1988-1998) for February (above) and August (below). Note how the distribution of highest precipitation migrates with the changing seasons. Original images courtesy of the Global Precipitation Climatology Project.

central Asia; Atacama, South America; central Australia). Descending air over the South Pole creates a cold desert in Antarctica where rainfall is no more plentiful than it is in Arizona. The world's lowest average annual precipitation is 0.075 centimeters (0.03 inches) and occurs in Arica, Chile, in the Atacama Desert. That's less than 5 centimeters (2 inches) of rain in the 59-year record of precipitation at the site.

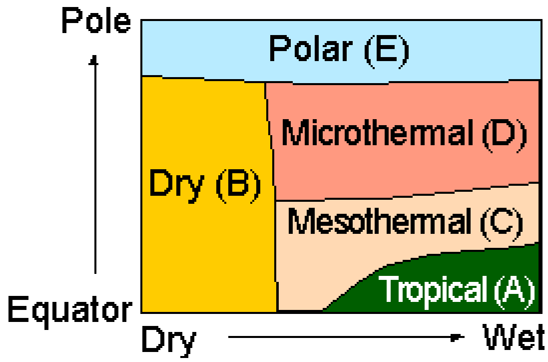
Think about it . . .
What features could you use to identify the climate of a region if you couldn't use weather data like temperature and precipitation?

Climate Regions

- Climate regions can be identified as areas with similar climates.
- The Koppen-Geiger classification system recognizes six climate regions: tropical (A), dry (B), mesothermal (C), microthermal (D), polar (E), and highland (H).
- The classification system is based upon variations in temperature and precipitation.
- Five of the six climate regions can be identified in the lower 48 states.

Areas with consistent climates are grouped together in **climate regions**. Climate influences **ecosystems**, communities of plants and animals; therefore specific associations of organisms characterize many climate regions.

The **Koppen-Geiger classification system**, named after two climatologists, divides the globe into climate regions using average monthly temperatures, average monthly precipitation, and total annual precipitation values. The classification recognized six climate regions, each denoted by a letter (Fig. 9).



Climate Regions

Figure 9. Relationship between climate regions, geographic location, and precipitation. One climate region, Highland (H) characterized by high elevations, is not illustrated.

Letter	Name	Characteristics
A	Tropical	Wet, hot equatorial regions that cover about a third of Earth's surface. Monthly average temperature above 18°C (64°F). U.S. example, Key West, Florida.
B	Dry	Arid and semi-arid deserts and steppes; evaporation exceeds precipitation. U.S. example: Albuquerque, New Mexico (annual precipitation, 22 cm [9 inches]).
C	Mesothermal	Humid sub-tropical, may have dry summers. Warmest month above 10°C (50°F); coldest month above 0°C (32°F) but below 18°C (64°F). U.S. example, New Orleans, Louisiana.
D	Microthermal	Humid climate with long winters, mild summers. Warmest month above 10°C (50°F); coldest month below 0°C (32°F). U.S. example, Flint, Michigan.
E	Polar	No true summer, warmest month average temperatures below 10°C (50°F); always cold. U.S. example, Barrow, northern Alaska.
H	Highland	Lower temperatures and more precipitation. U.S. example, Blue Canyon, Sierra Nevada, California (annual precipitation, 170 cm [68 inches]).

Further divisions of the classification system are identified by adding lowercase letters. For example Af designates tropical rain forest; Am is tropical monsoon with a marked dry season of one or more months; Aw is tropical savanna with a winter dry season. For the purposes of *The Good Earth* we will identify only the six classes above.

Five of the six climate regions can be identified in the lower 48 states with the dry (B) and mesothermal (C), and microthermal (D) climate classes covering the largest areas. Where would we look within the U.S. to find an example of the missing climate region?

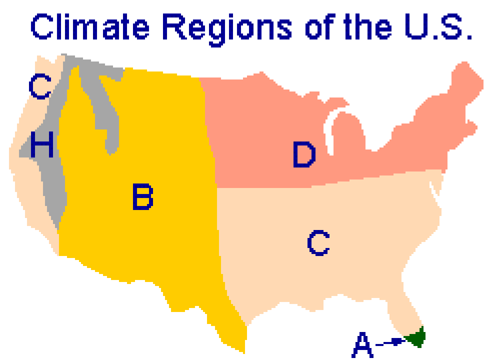


Figure 10. A simplified map of the main climate regions of the continental U.S.

Think about it . . .
Which climate region do you live in?

Climate History

- Viking settlement of Greenland was influenced by climate fluctuations.
- Temperatures were above normal during the Medieval Warm Period and below normal during the Little Ice Age
- Air bubbles trapped in glacial ice reveal the composition of the earlier atmosphere.
- Recent climate has been dominated by an ice age.
- The ice age is divisible into short warm interglacials, and longer colder glacials.
- Carbon dioxide concentrations are greater during warm periods.
- Civilization arose during the most recent warm interglacial interval, the Holocene.

Climate has fluctuated throughout Earth history. Some fluctuations occurred on time scales measured in millions of years; others lasted for centuries. Many scientists believe that Earth's climate is currently undergoing a warming trend induced by human activities. Before we can thoroughly characterize recent climate changes we must first examine past climates and identify their signatures and rates of change. This section examines a relatively short-lived warming trend that began in the Northern Hemisphere at the start of the last millennium (~1,000 A.D.) and evidence of changing climates during the last major ice age that ended approximately 10,000 years ago.

The Vikings in Greenland

Archeological, historical, and geologic records indicate that changes in climate patterns influenced the distribution of past civilizations. One example of this phenomenon is the Viking colonization of North Atlantic islands (Fig. 11).

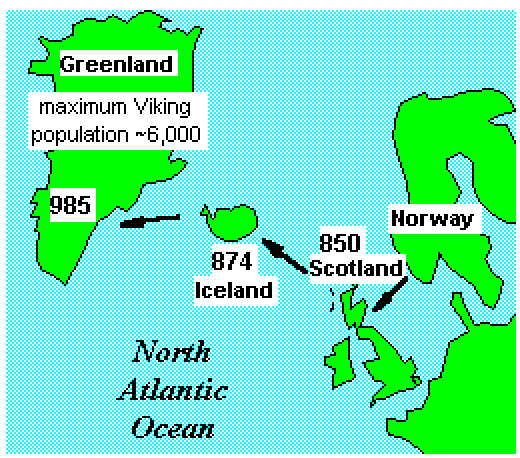


Figure 11. Timing of migration of Viking settlers from Norway to Greenland. A warming trend resulted in an absence of pack ice in the North Atlantic and allowed the Vikings to settle Greenland.

The Vikings migrated from Scandinavia approximately a thousand years ago, during a period of warmer temperatures when the North Atlantic pack ice melted. Viking settlement moved progressively westward between ~850 to 985 A.D. from Scottish islands (Shetland, Hebrides) to Iceland and finally Greenland (Fig. 11). Higher temperatures increased the length of the Greenland growing season sufficiently to support grasses needed for grazing animals.

However, climate began to reverse itself a few centuries later, passing from the relative warmth of the **Medieval Warm**

Period (MWP, 900-1400) to the colder temperatures of the **Little Ice Age** (LIA, 1400-1850; Fig. 12). As temperatures declined, so too did the Viking's agricultural base. Although they came in contact with native **Inuit** from the north, they did not adopt Inuit means of food production (hunting with harpoon), boat building (using skins rather than rare wood), or clothing (skins instead of wool). Consequently, the Vikings became increasingly maladapted to the changing climate and the colony died out in ~ 1450.

Climate change did not lead to the extinction of the Norse colony on Greenland, but it did make the landscape more hostile, requiring greater social flexibility than was evident in the relatively rigid Viking culture. The rate of temperature change on Greenland from the MWP to the LIA was about 1^{o}C per 50 years, twice as rapid as the rate of temperature increase over the last century.

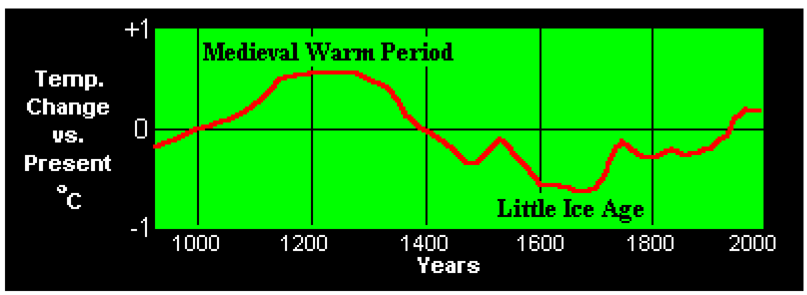


Figure 12. Difference between present temperatures and temperatures during the last millennium. Temperatures declined by 1.5^{o}C from the MIA to the LIA, severely limiting agriculture on Greenland.

Recent Climate Changes

Climate fluctuations during the recent history of the earth can be determined from the analyses of air bubbles, oxygen isotopes, and pollen from ice cores from Greenland and Antarctica, and from microfossils in sediment cores collected from the ocean floor (see Records of Climate Change).

Climatic evidence indicates that the Northern Hemisphere experienced widespread glaciation during the last two million years. This Ice Age is divisible into long (~100,000 year) cold intervals (**glacials**) and short (~20,000 year) warm intervals (**interglacials**). The climate of North America was dominated by the presence of a massive continental ice sheet centered over Canada. Global temperatures increased rapidly approximately 10,000 years ago (Fig. 13) as the world entered the most recent interglacial interval (called the Holocene). Shorter variations that may last for hundreds of years (e.g., MWP, LIA) are superimposed on these relatively uniform fluctuations between warm and cold.

Recent investigations have linked temperature variations with changes in atmospheric chemistry. Higher levels of the greenhouse gases carbon dioxide and methane match high temperatures during the most recent interglacials (Fig. 13). There appears to be a strong correlation between carbon dioxide levels in the atmosphere and global temperatures. Information extracted from ice cores spanning the last 160,000 years illustrates that temperature varied within an 8°C range. Warm temperatures correlate with periods of higher carbon dioxide concentrations (280 ppm) and intervening cold periods match lower carbon dioxide levels (200 ppm).

Temperatures were lowest approximately 15,000 years ago during the height of the last glacial. The landscape of North America would have looked considerably different than present:

- A **thick ice sheet** covered almost all of Canada and extended south into the U.S. around the Great Lakes.

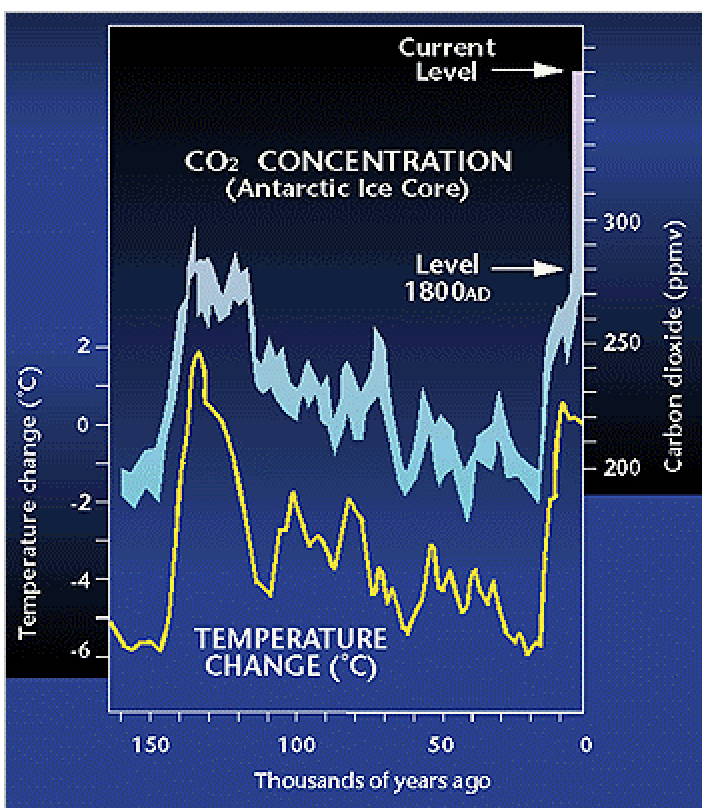


Figure 13. Temperature change and carbon dioxide concentration during the last 165,000 years. Temperatures were lower during the cold glacial interval (from 140,000 - 10,000 years ago), and were higher during the warmer interglacial intervals. Higher carbon dioxide concentrations were associated with the warmer interglacial intervals. Image courtesy of Whitehouse Climate Change website.

- **Sea level was lower** (much of the water was trapped as ice) so the continent was larger.
- Lower sea levels resulted in a **land bridge** between Siberia and Alaska.
- The **eastern U.S. was forested**. Forests became more open to the west.
- The western U.S. had an arid or semi-arid climate with associated desert but the low temperatures resulted in a **cold polar desert** (precipitation is very low in polar regions).

The rise of civilization occurred exclusively during the Holocene. For much of this time, Earth was adjusting to the melting ice sheets; sea level was gradually rising, rivers built deltas, expanding the shoreline as sea level stabilized; tundra was replaced by conifer forests; and conifer forests were replaced by deciduous woodlands. Our ancestors spread out to occupy the newly temperate lands of Europe, North America, and Asia. The planetary geography and biology that we are so familiar with represents just the latest stage in this evolving picture.

Records of Climate Change

- Long-term (millions of years) proxy records are represented by oxygen isotope ratios.
- Examples of short-term (thousands of years) proxy climate indicators are pollen, oxygen isotopes, and tree ring data.

Climate fluctuations during the history of the earth can be determined from the analyses of a variety of biological and geologic data sources. Some allow the reconstruction of climates stretching back millions of years, others provide precise annual records that cover the advance of human civilizations. These data represent **proxy records** of paleoclimates - data that can be interpreted to give indirect information on past climates (Fig. 14).

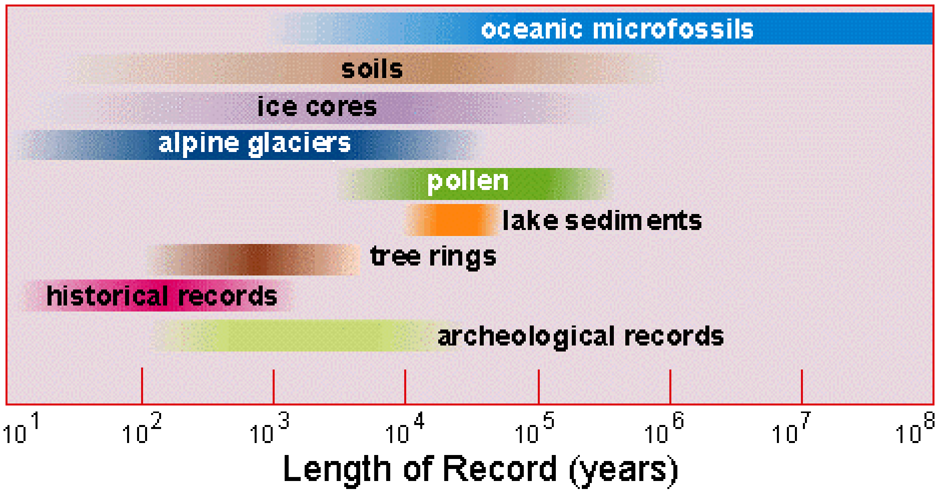


Figure 14. Paleoclimatic data come in a variety of forms; some give information on long-term climates (oceanic microfossils); others provide precision in the recent, short-term climate record (tree rings, pollen).

Long-term Climate Changes

Changes in temperature over millions of years can be determined using **oxygen isotopes** (oxygen atoms with different numbers of neutrons). Two isotopes of oxygen, ^{16}O (lighter, more abundant) and ^{18}O (heavier, less abundant), are present in ocean water. These isotopes are preserved in the **ice** of Greenland and Antarctica and are incorporated into the skeletons of **microscopic organisms** that dwell in the oceans.

Water that evaporates from the oceans is relatively enriched in the lighter ^{16}O isotope. During cold periods when the polar ice sheets expanded, much of this water vapor was converted to ice, leaving the oceans smaller and relatively enriched in ^{18}O. In contrast, warm periods are characterized by melting glaciers that return more of the ^{16}O isotope to the ocean, increasing ^{16}O concentrations. During normal (equilibrium) conditions, ^{16}O is lost by evaporation but is returned to the oceans as precipitation, resulting in no net change in the oxygen isotope ratio. As ice sheets expand, the relative volume of ^{16}O in the ocean decreases, driving up the $^{18}O/^{16}O$ ratio (Fig. 15). When the ice melts the ^{16}O is returned to the oceans, causing the ratio to decline.

The ratio of $^{18}O/^{16}O$ in ancient ice or in organism's skeletons can be compared with standard values. The difference can be used to estimate the temperature of the air in which the ice (snow) was precipitated or of the water in which the microscopic organisms grew. The ratio acts as a paleothermometer for ancient climates. The $^{18}O/^{16}O$ ratio is

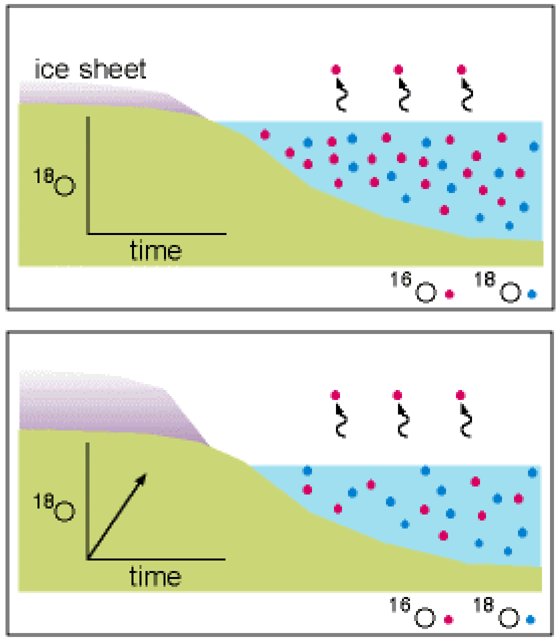


Figure 15. The lighter ^{16}O isotopes evaporate with sea water (above) and are incorporated into continental ice sheets causing the oceans to become enriched in the ^{18}O isotope (below).

higher at lower temperatures (when oceans are enriched in ^{18}O), and decreases as temperatures increase. This relationship has been used to interpret climate conditions during the Cenozoic era, representing the last (most recent) 66 million years of geologic time.

The Earth was much warmer 52 million years ago. Scientists have discovered that the temperature contrast between the equator and poles was much less than at present. Much of the southern U.S. would have experienced a tropical climate. Islands in northern Canada contain fossils of alligator-like reptiles from this period. This warm interval was followed by a long cooling trend from 52 to 36 million years ago. Increasing $^{18}O/^{16}O$ ratios in marine microfossils reflect the development of permanent ice caps in East Antarctica and a drop in southern ocean surface temperatures to 5 to 8^{o}C.

Global temperatures fluctuated between 36 to 20 million years ago and had a short warming trend from 20 to 16 million years ago, before another dramatic drop in temperature between 16 to 10 million years. This mega-cold snap resulted in the development of glaciers on Greenland. There was a brief warming from 5 to 3 million years ago that was followed by a third cooling episode that continued to the present.

Short-term Climate Changes

Pollen: Plants produce pollen grains that collect in sediment on the bottom of ponds, lakes, and oceans. Pollen can be analyzed from cores of sediments and can be used to obtain records of changing plant communities that reflect decade-scale climate changes stretching back several thousand years (Fig. 16). For example, a dramatic cold period in Europe approximately 11,000 years ago (called the Younger Dryas) was marked by the appearance of the pollen of the polar wildflower *Dryas octopetala* in sediments (Fig. 17).

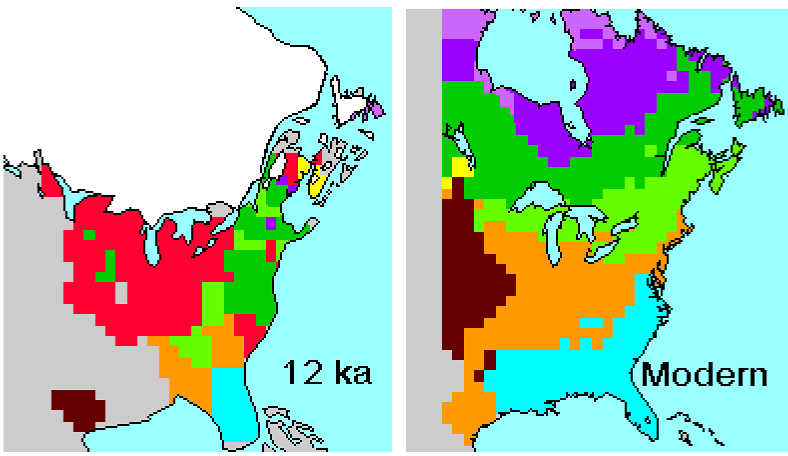


Figure 16. Vegetation distribution 12,000 years ago and today based upon pollen data. Dark green = evergreen forest; light green = mixed forest; orange = deciduous forest; black = prairie; purple = tundra; red = no equivalent modern species. Large white area in left figure is extent of the continental ice sheet. Graphic modified from NOAA Paleoclimatology Program image.

Oxygen isotopes: Oxygen isotope ratios in modern corals reveal temperature changes over periods up to hundreds of years on a year-decade scale that cannot be distinguished in long-term climate change events. Oxygen isotopes in ice cores drilled from Antarctica and Greenland can provide a detailed climate history extending back over 200,000 years. Individual ice layers can be dated much like tree rings to determine their age and the air bubbles trapped within each layer are used to learn about climate variations. Dust and pollen particles trapped in the ice also yield clues to ancient climates.

Dendrochronology (tree rings research): Relatively short-term climate change can also be distinguished from tree ring records. Live trees add a new growth ring each year, therefore counting the rings in a dead tree reveals its age. The width of the rings can be used to decipher precipitation history during tree growth; wide rings occur during wet, warm years, narrow rings during cool or dry years. A single Huon Pine tree from Tasmania, Australia, was 2,200 years old and revealed climate fluctuations from 270 B.C. to 1973. Records for several trees

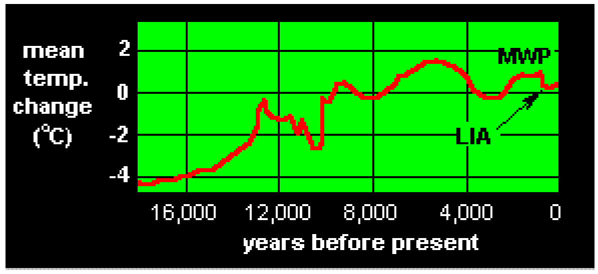


Figure 17. Graph of temperature changes during last 18,000 years illustrates the rapid drop in temperature during Younger Dryas event (~11,000 years ago) and the smaller changes associated with the Little Ice Age (LIA) and Medieval Warm Period (MWP).

were used to graph temperature fluctuations over the last 1,100 years. Scientists can use tree rings to determine climate conditions up to 8,000 years ago by matching tree ring patterns from trees of different ages.

Recently published tree ring data reveals that the twentieth century was the warmest of the last 600 years and that very short term climate fluctuations (1-5 years) were the result of large-volume volcanic eruptions that prompted periods of global cooling.

Causes of Climate Change

- Long-term (millions of years) climate changes are linked to plate tectonic processes
- Short-term (thousands of years) changes are associated with changes in Earth's orbit

The cause of such **long-term global climate changes** has to be processes that operate on a global scale over very long time intervals. The most likely causes are associated with the changing locations of continents and oceans (plate tectonics) that would in turn affect atmospheric and oceanic circulation patterns.

For example, ice ages have occurred at four widely separated times in Earth's history from the Precambrian (700 million years ago) to the recent past (~10,000 years ago). The causes of such events are thought to be linked to global-scale processes. Some potential requirements for such long-term cooling events may be:

1. **Continents near poles**: Continental ice sheets that are characteristic of ice ages can only form on land. Glaciation

on the ancient supercontinent, Pangaea, occurred when several continents were grouped around the South Pole.

2. **Uplift associated with continental collisions**: One tectonic element that is thought to have contributed to global cooling beginning about 40 million years ago is the formation of the Himalaya Mountains. Some scientists have suggested that the mountains changed the regional (maybe even global) atmospheric circulation patterns that contributed to a cooler climate.
3. **Reduction in greenhouse gas concentrations**: Increased rainfall following uplift may have stripped carbon dioxide from the atmosphere to be used in chemical weathering. The presence of less carbon dioxide resulted in a reduction in global warming (i.e., a cooling event).

Times in the geologic past when temperatures where much higher than today are related to periods of more rapid plate movements and greater volcanic activity. Both processes produced greater volumes of greenhouse gases that caused long-term warming of the atmosphere.

Short-term climate fluctuations that occur on cycles lasting thousands of years are related to variations in Earth’s orbit around the Sun. These variations, termed **Milankovitch cycles** after the astronomer who identified them, cause the amount of incoming solar radiation to vary with time.

1. The **eccentricity** of Earth’s orbit. The exact path of the orbit around the Sun changes with time and may become less eccentric (more circular) or more eccentric (more elliptical). These changes occur on a 100,000-year cycle.
2. Changes in the **tilt** of Earth’s axis. The tilt of Earth's axis is currently tilted at 23.5 but axial tilt ranges from approximately 22 to 25 degrees over a 41,000-year cycle. Decreasing tilt reduces the contrast of insolation associated with the seasons, increasing tilt exaggerates seasonal differences. Lesser tilt promotes the buildup of ice at the poles, greater tilts allow for more insolation during polar summers, causing more snow melt.
3. The **precession** of Earth on its axis: Earth "wobbles" on its axis (precession), changing the direction of axial tilt. Precession occurs on a 26,000-year cycle - the length of time taken for the axis to trace a complete loop. Halfway through the precession cycle, Earth would be tilted away

from the Sun during the "summer" solstice (Northern Hemisphere) and the Sun would be overhead at the Tropic of Capricorn. Maximum precession therefore results in a switch between summer and winter seasons, with the warmest months occurring in what we now call winter and cooler months during our the middle of the year (Fig. 18).

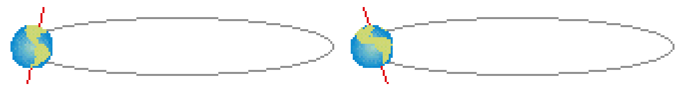


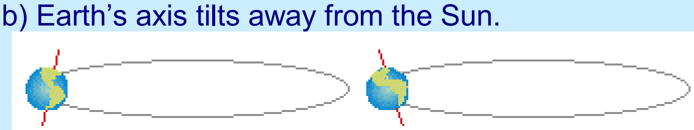
Figure 18. Precession results in the seasons alternating position as the Sun will be overhead at the Tropic of Capricorn (Southern Hemisphere summer) during the middle of the year (Northern Hemisphere summer).

All of these factors contribute to changes in the amount of solar radiation that reaches Earth and the amount of heat that is transferred from the Sun. During ice ages these cycles correlate well with jumps from cold intervals (**glacials**) to warmer intervals (**interglacials**). However, the variations in solar radiation are not considered sufficient to account for the magnitude of observed temperature variations.

Cooler temperatures during the glacials were associated with lower concentrations of carbon dioxide (a heat-trapping gas) and higher levels of atmospheric dust (blocked incoming sunlight). What is less clear is how these factors are linked to variations in Earth's orbit. Climate fluctuations that occur on even shorter time scales (decades to centuries) may be linked to variations in **sun spot activity** or catastrophic **volcanic eruptions**.

Think about it . . .

1. What change in the tilt of Earth's axis would decrease July temperatures in the Northern Hemisphere?
   a) Tilt increases to 26 degrees.
   b) Tilt decreases to 21 degrees.
2. What change in the eccentricity of Earth's axis would decrease July temperatures in the Northern Hemisphere?
   a) Earth is further from the Sun.
   b) Earth is closer to the Sun.
3. What change in the precession of Earth's axis would decrease July temperatures in the Northern Hemisphere?
   a) Earth's axis tilts toward the Sun.
   b) Earth's axis tilts away from the Sun.



Summary

1. What is the difference between weather and climate?
Weather is the state of the atmosphere for a short time whereas climate represents average weather conditions over a long time period. For example, weather might give us a warm day in January but climate tells us that January is typically a cold month.

2. What is the principal control on global climate patterns?
The amount of incoming solar radiation (insolation). Temperatures increase with more insolation and decrease with less insolation. Insolation is greatest at the equator and least at the poles. Consequently, temperatures decrease with increasing latitude.

3. Why is the Northern Hemisphere colder in winter than in summer?
The principal reason for the seasonal differences in climate around the globe is the tilt of Earth's axis. Earth rotates around an axis that is tilted 23.5 degrees to vertical. Insolation is greatest when the Sun is directly above a location on Earth and decreases as the angle of the Sun's rays becomes more oblique. The axial tilt places the Sun directly overhead at the Tropic of Cancer in the Northern Hemisphere during the summer solstice (June 21). Likewise, the Sun's rays strike the Northern Hemisphere more obliquely when the Sun lies over the Tropic of Cancer in the Southern Hemisphere during the winter solstice (December 21).

4. What drives the global atmospheric circulation system?
The contrast between insolation at the equator (more insolation) and the poles (less insolation) generates a heat gradient that results in rising air at the equator and sinking air at the poles. This simple convection model is disrupted into three separate cells by the effect of Earth's rotation. Winds associated with the convection cells make up the circulation system.

5. How is circulation in the Hadley convection cell related to climate over the equator and tropics?
The atmosphere above the equator receives 2.5 times more incoming solar radiation than the atmosphere above the poles. This warmed air rises and the humidity of the air increases as it cools during its ascent. This results in condensation, cloud formation, and precipitation. Equatorial regions are

characterized by warm temperatures and heavy rainfall (e.g., tropical climate). This air then moves north or south before beginning to descend above the tropics (20-35 degrees latitude). The descending air becomes warmer and dryer as it approaches Earth's surface, preventing condensation and resulting in clear skies over the tropics. The descending air flows toward the equator, forming the last leg in the convection cell. These winds are deflected to the west (right) in the Northern Hemisphere and to the east (left) in the Southern Hemisphere because of the Coriolis effect and are known as the trade winds.

6. How are the convection cells related to cloud cover?

Clouds form where ascending (cooling) air occurs between adjoining convection cells and clear skies occur when air descends (warms). Ascending air is found above the equator and at the Polar front (between the Ferrel and Polar cells) and these regions are characterized by cloudy conditions. In contrast, clear skies are located in regions of descending air such as the tropics below (between the Ferrel and Hadley cells) and over the poles.

7. Why are continental temperatures more extreme than temperatures for the oceans at the same latitude?

The mixing of ocean currents results in less extreme temperatures in oceans adjacent to land masses. High temperatures in the deserts of North Africa may be 10^oC more than the adjacent Atlantic Ocean. Likewise, the extreme cold temperatures (-50^oC) of the Antarctic interior is not matched in the waters of the Southern Ocean where temperatures remain a few degrees above freezing.

8. Where are temperature and precipitation greatest?

The highest average global temperatures are typically found between the tropics and the equator and decrease progressively toward the poles. Precipitation is also greatest along the equator and is typically least at the tropics and the poles.

9. How are climate regions identified in the Koppen-Geiger classification system?

The system considers three parameters: (a) average monthly temperatures; (b) average monthly precipitation; and (c) total annual precipitation.

10. Can climate regions be differentiated by latitude?

Four are typically identifiable by latitude. Beginning at the equator and moving toward the poles the climate regions in order are: tropical, mesothermal, microthermal, and polar. Dry and highland climates are specific cases.

11. How did climatic changes influence the Viking's colonization of Greenland?

Viking settlement of Greenland occurred when temperatures in the North Atlantic region rose approximately 900 years ago at the start of the Medieval Warm Period. Unfortunately, temperatures began to decline about 500 years later at the beginning of the Little Ice Age and the Vikings were not able to adapt to living in a colder climate.

12. How has the climate of the Northern Hemisphere changed during the recent geologic past?

The climate of the Northern Hemisphere was dominated by the presence of a massive continental ice sheet during the last two million years. This period was known as an ice age and was divisible into long (~100,000 year) cold intervals (glacials) and short (~20,000 year) warm intervals (interglacials). Glacials were up to $8^{o}C$ colder than the interglacials and warm temperatures correlated with periods of higher carbon dioxide concentrations. Global temperatures increased rapidly approximately 10,000 years ago as the world entered the most recent interglacial (the Holocene). The rise of civilization occurred during the Holocene.

13. How do we know what the climate was like in the past as there were no instruments (or people) to measure climate parameters?

Climate fluctuations during the history of Earth can be determined from the analyses of a variety of proxy records, data that can be interpreted to give indirect information on past climates. Paleoclimatic data come in a variety of forms, some give information on long-term climates (oceanic microfossils); others provide precision in the recent, short-term climate record (tree rings, pollen).

14. How can we determine climate characteristics in the long-term geologic record, stretching back hundreds of thousands, or even millions of years?

Changes in temperature over millions of years can be determined using oxygen isotopes (oxygen atoms with different numbers of neutrons). Two isotopes of oxygen, ^{16}O (more abundant) and ^{18}O (less abundant), are present in ocean water. These isotopes are preserved in the ice of Greenland and Antarctica and are incorporated into the skeletons of microscopic organisms that dwell in the oceans. The ratio of $^{18}O/^{16}O$ in ancient ice or in organism's skeletons can be compared with standard values. The difference can be used to estimate the temperature of the air in which the ice (snow) was precipitated or the temperature of the water in which the organisms grew. The ratio acts as a paleothermometer for ancient climates. The $^{18}O/^{16}O$ ratio is higher at lower temperatures (when oceans are enriched in ^{18}O), and decreased as temperatures increased.

15. How can we determine climate characteristics in the short-term geologic record over the last 10,000 years?

Short-term climatic changes can be identified on some of the longest historical records (Norse saga, European agricultural records, Chinese weather descriptions), archeological discoveries, tree ring evidence, pollen characteristics, and oxygen isotope records of coral. Pollen reveals plant assemblages that are linked to climate patterns and tree ring research provides evidence of wet and dry years.

16. How do current temperatures compare with those of the geologic past?

Average global temperatures have fluctuated in the geologic past. Earth was warmer than today for the majority of the last 60+ million years but was cooler during the recent ice age that ended approximately 10,000 years ago.

17. Why have climates changed throughout the geologic past?

The cause of long-term global climate changes has to be linked to processes that operate on a global scale over millions of years. The most likely causes are associated with the changing locations of continents and oceans that would in turn affect atmospheric and oceanic circulation patterns. More rapid plate motions may be linked to warmer climates and widespread uplift associated with continental collisions may have contributed to global cooling events.

18. What causes variations in climate over intervals of thousands of years?

Short-term climate fluctuations are related to variations in Earth's orbit (Milankovitch cycles) that cause the amount of incoming solar radiation to vary. These variations result from changes in the shape of Earth's orbit and changes in the magnitude and direction of tilt of Earth's axis.