Temperature Over Time

Module Overview

In this module, you will investigate whether Earth is warming. First, you will review the causes of seasonal and daily temperature changes at different latitudes and locations. You will then analyze a variety of temperature data to compare temperature trends over different time periods (from decades to centuries) and over different spatial scales (from local to global). These investigations will help you answer whether the recent rise in Earth's global mean temperature (GMT) is unusual.

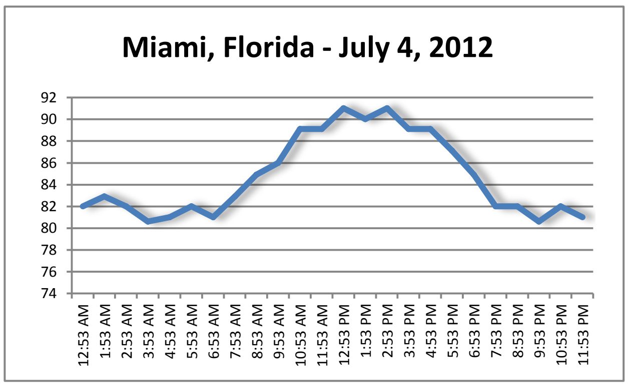
When you complete this module, you will be able to

- Explain how Earth's tilt and orbit cause the seasons and the variation in temperature at different latitudes.
- Differentiate between the factors that cause changes in temperature.
- Explain the main factors, other than latitude, that cause variations in temperature at different locations.
- Compare and contrast temporal (time-based) temperatures trends.
- Compare and contrast spatial (geographic-based) temperatures trends.

Why Temperature Varies

You have learned that the global mean temperature is controlled by the balance of incoming energy from the sun and outgoing energy from Earth. However, as you also know, temperature varies from one location to another. What accounts for this variability? The temperature in a certain place is influenced by four main factors. The most important factor is a location's latitude, which is the angular distance, expressed in degrees and minutes, north or south of the equator. Other factors include the location's proximity to a body of water, the temperature of ocean currents (if the location is near the coast), and the location's elevation above sea level.

Latitude and the Seasonal Temperature

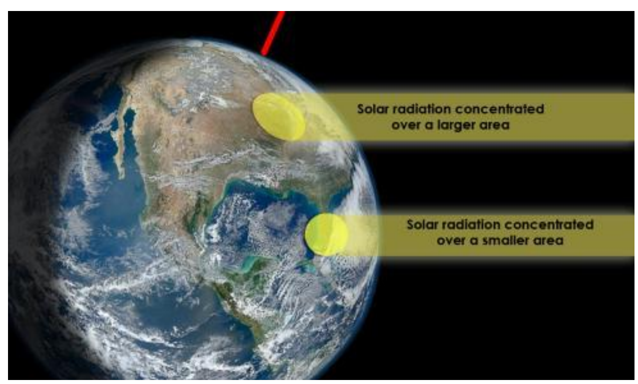


Data Source:* *Weather Underground

You are already familiar with daily variations in temperature. Daily air temperatures at Earth's surface are controlled by the incoming and outgoing energy. During the day, the air temperature increases as energy gains exceed the energy lost from Earth's surface (mainly through the processes of convection and radiation). Throughout the night, the air temperature decreases as Earth's surface loses more energy than it receives. This variation in daily temperatures for a specific location is influenced by the angle of the sun's rays and the number of daylight hours at that location. Both the angle of the sun's rays and the number of daylight hours in a location change throughout the year as Earth orbits or revolves around the sun.

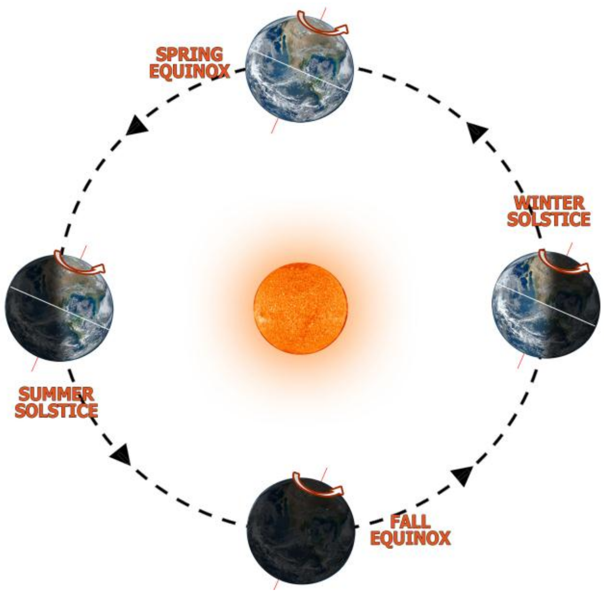
Angle of Solar Radiation and Temperature

The angle of incoming solar radiation influences seasonal temperatures of locations at different latitudes. When the sun's rays strike Earth's surface near the equator, the incoming solar radiation is more direct (nearly perpendicular or closer to a 90˚ angle). Therefore, the solar radiation is concentrated over a smaller surface area, causing warmer temperatures. At higher latitudes, the angle of solar radiation is smaller, causing energy to be spread over a larger area of the surface and cooler temperatures. Because the angle of radiation varies depending on the latitude, surface temperatures on average are warmer at lower latitudes and cooler at higher latitudes (even though higher latitudes have more hours of daylight during the summer months).



This graphic shows how the angle of the sun's rays can affect temperature. *Earth Image Source: NASA*

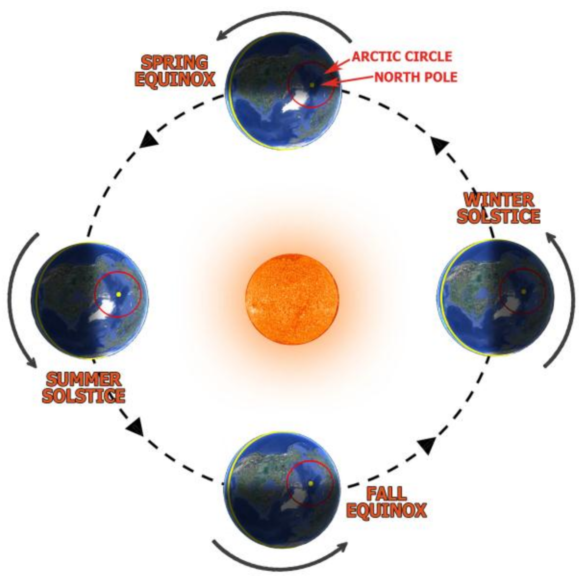
The University of Nebraska's Daylight Simulator is a simulation showing daylight and nighttime regions on Earth throughout the day and year.
http://astro.unl.edu/classaction/animations/coordsmotion/daylightsimulator.html



This graphic shows Earth with its 23.5° tilt, the direction of its rotation and the pattern of the seasons as it travels around the sun. This is a horizontal perspective facing the equator. ***Image Source: NASA (Earth & Sun)***

The Seasons

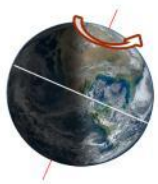
Like the other planets, Earth rotates on its axis as it revolves around the sun. Earth takes 365 and ¼ (6 hours) days to complete one revolution around the sun. To keep our calendars synchronized with the planet's actual orbit, every 4 years we add an extra day to the month of February – 4 quarters of a day (1 quarter each year for 4 years) equals 1 day or 24 hours. When we add a day every 4 years to align the calendar, this year is often called a leap year.



Similar to the previous graphic but this perspective is vertical and looking down at the North Pole. ***Image Sources: Google Earth & NASA (Sun)***

At the present time, Earth is tilted on its axis of rotation by 23.5°. The direction and angle (or tilt) of Earth's axis of rotation do ***not*** change as Earth revolves around the sun. Because the direction and angle of the axis of rotation do not change, the Northern Hemisphere is tilted toward the sun during part of the year and away from the sun during another part of the year.

People often mistakenly think that the different seasons are caused by a change in Earth's distance from the sun. This is a misconception because Earth's orbit is only slightly elliptical and our planet is nearly the same distance from the sun all year long. Earth is actually a little farther from the sun when the Northern Hemisphere is having summer. Whichever hemisphere (the Northern or Southern Hemisphere) is tilted toward the sun receives more direct rays of sunlight (or rays that are closer to perpendicular or a 90° angle). The hemisphere tilted toward the sun also has more hours of daylight than the hemisphere that is tilted away from the sun. The combination of more direct rays of sunlight and more hours of daylight causes the hemisphere tilted toward the sun to receive more solar radiation and to have warmer temperatures. When the Northern Hemisphere is tilted toward the sun, latitudes between the equator and 90°N (the North Pole) are experiencing summer. At the same time, the Southern Hemisphere is tilted away from the sun and experiencing winter.


SUMMER SOLSTICE

The summer season begins in the Northern Hemisphere on June 20 or 21, known as the summer solstice, when the axis of rotation is tilted a full 23.5° toward the sun. The incoming solar radiation strikes Earth directly at a perpendicular or 90° angle to the 23.5°N parallel of latitude. This 23.5°N parallel of latitude, which runs through Mexico, the Bahamas, Egypt, Saudi Arabia, India, and southern China, is known as the Tropic of Cancer. On the summer solstice, the Northern Hemisphere has the greatest number of daylight hours, whereas the Southern Hemisphere has the fewest. The angle of the sun above Earth's Northern Hemisphere is greatest on this day. Because Earth is tilted toward the sun, the North Pole remains on the daylit side of the Earth throughout the entire day resulting in 24 hours of daylight, whereas the South Pole (which is tilted away from the sun) has 24 hours of darkness. The North Pole has 24 hours of daylight from spring to fall equinox and the South Pole has 24 hours of darkness during that period. This reverses on the equinoxes, so the poles actually only have one sunrise and one sunset per year (on the equinox). After the passing of the summer solstice, the length of daylight in the Northern Hemisphere gradually decreases, while the length of daylight in the Southern Hemisphere begins gradually increases.

Fall or autumn in the Northern Hemisphere begins September 22 or 23. Remember that the tilt and direction of Earth's axis of rotation is the same as Earth revolves around the sun. On the first day of fall, Earth is neither tilted toward nor away from the sun, causing the length of daylight and nighttime hours to be equal (12 hours) in both hemispheres. This day is often referred to as the fall or autumn equinox. In the Southern Hemisphere, spring begins on this day. Throughout the Northern Hemisphere's fall season, the length of daylight gradually decreases until the first day of winter.


FALL EQUINOX

WINTER SOLSTICE


Winter in the Northern Hemisphere begins on December 21 or 22, when the axis of rotation is tilted a full 23.5° away from the sun. On this day, known as the winter solstice, the incoming solar radiation strikes Earth directly at a perpendicular or 90° angle to the 23.5°S parallel of latitude, known as the Tropic of Capricorn. Therefore, the sun's rays strike the Northern Hemisphere at the smallest angle.

On December 21 or 22, the sun appears to be at lowest point on the horizon, and the Northern Hemisphere has the fewest number of daylight hours. In the Southern Hemisphere, this is the day with the greatest number of daylight hours and the beginning of summer. The North Pole has 24 hours of darkness, whereas the South Pole has 24 hours of daylight. After the winter solstice, the length of daylight gradually begins to increase in the Northern Hemisphere and decrease in the Southern Hemisphere.

Spring in the Northern Hemisphere begins on March 20 or 21 when Earth is again not tilted toward or away from the sun. On this day, known as the spring equinox, there are 12 hours of daylight and 12 hours of darkness in both hemispheres. Fall begins on March 20 or 21 in the Southern Hemisphere. The length of daylight in the Northern Hemisphere continues to increase until the first day of summer.

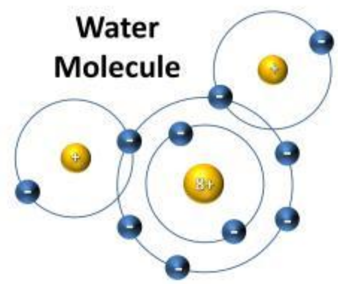
The University of Nebraska's Seasons Simulator is an interactive animation of the seasons. You can change your latitude and angle of the sun's rays over the course of the year.

University of Nebraska

http://astro.unl.edu/classaction/animations/coordsmotion/eclipticsimulator.html

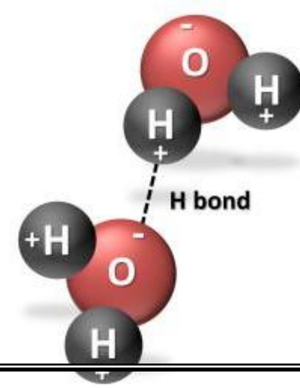
Water Influence on Temperature

One unique property of water is its high heat capacity – the highest of all liquids other than liquid ammonia. This property is due to the hydrogen bond between water molecules. The following explanation about water molecules will help you understand why coastal areas tend to have more moderate temperatures.



A water molecule consists of one oxygen (O) atom bonded to two hydrogen (H) atoms. The "8+" refers to the atomic number of oxygen, which is also the number of protons in the nucleus and number of electrons in the energy levels outside the nucleus. For the oxygen atom, 2 electrons are in the first energy level and the remaining 6 electrons are in the next or second energy level. Hydrogen has an atomic number of 1, which means that hydrogen has one proton in the nucleus and one electron in the lowest energy level outside the nucleus. The second energy level can hold 8 electrons, so each hydrogen atom shares its 1 electron with the oxygen atom, completing the second energy level and making a water molecule.

The bonding between the oxygen atom and each hydrogen atom is known as covalent bonding because they share electrons to make a very stable water molecule. The two hydrogen atoms are bonded to the oxygen atom at a 105° angle. This geometry of the water molecule causes it to have positively and negatively changed ends, known as polarity. Water is referred to a polar or dipolar molecule. The large nucleus of the oxygen atom attracts the shared electrons causing this side of the water molecule to be negatively charged while the hydrogen side is positively charged. This polarity allows water to bond easily with adjacent water molecules. The hydrogen bond is the bond between two water molecules.



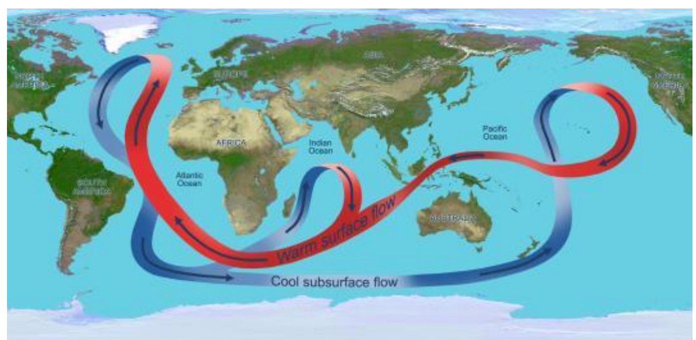
Water is a liquid rather than gas (or water vapor) at room temperature because of the strong hydrogen bond between the molecules of water. (This strong bond causes water to resist molecular motion and remain a liquid at room temperature.) This means that it takes more energy or heat to increase water's temperature than it does for most other substances. Specific heat is the amount of heat energy it takes to raise or lower the temperature of 1 gram of a substance by 1°Celsius. The specific heat of liquid water is 1 calorie per gram per 1 degree C (cal/g/°C). The specific heat of water is greater than that of dry soil, therefore water both absorbs and releases heat more slowly than land.

Water also is fluid, allowing the heat to be mixed to greater depth than on land. The heat capacity is the product of the specific heat and the mass (in g) of the material. Oceans have a greater heat capacity than land because the specific heat of water is greater than that of dry soil and because a mixing of the upper ocean results in a much larger mass of water being heated than land. This causes land areas to heat more rapidly and to higher temperatures and also cool more rapidly and to lower temperatures, compared to oceans.

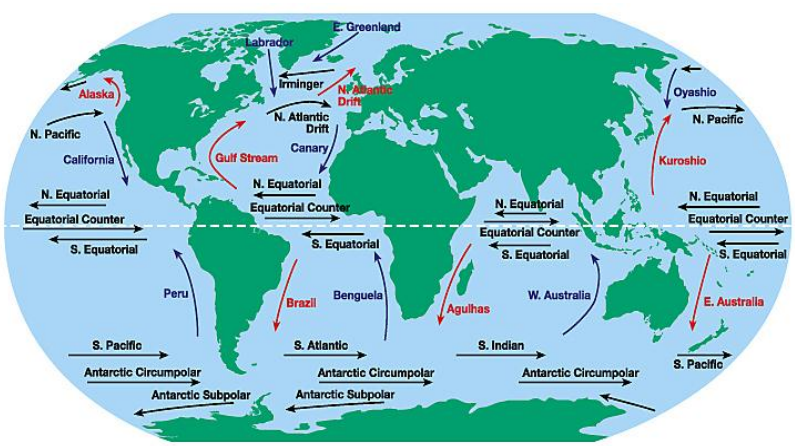
The high heat capacity of water also explains why the temperatures of land near a body of water are more moderate. The high heat capacity of water keeps its temperature within a relatively narrow range, causing nearby coastal areas to also have a smaller daily and seasonal temperature range. In contrast, areas with similar weather conditions that are farther from the coast tend to have a much wider range of seasonal and daily temperatures. To summarize, large bodies of water tend to moderate the temperature of nearby land due to the high heat capacity of water. This high heat capacity results from both the higher specific heat of water and the mixing of heat throughout a greater depth over oceans.

Ocean Currents

Surface ocean currents have a strong effect on Earth's climate. Areas near the equator receive more direct solar radiation than areas near the poles. However, these areas do not get continually warmer and warmer, because the ocean currents and winds transport the heat from the lower latitudes near the equator to higher latitudes near the poles.



This illustration depicts the overturning circulation of the global ocean. Throughout the Atlantic Ocean, the circulation carries warm waters (red arrows) northward near the surface and cold deep waters (blue arrows) southward. *Image Credit:* *NASA/JPL*



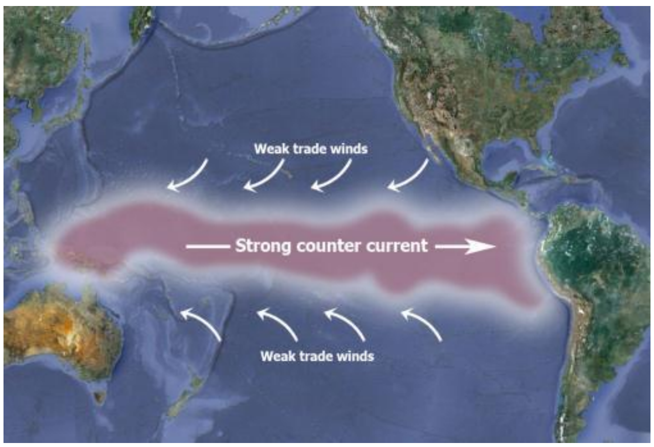
The water of the ocean surface moves in a regular pattern called surface ocean currents. On this map, warm currents are shown in red and cold currents are shown in blue. *Image Credit:* Windows to the Universe

Large quantities of heat can be absorbed and stored in the surface layers of the ocean. This heat is transported by ocean currents. In this way, the ocean currents help regulate Earth's climate by facilitating the transfer of heat from warm tropical areas to colder areas near the poles.

The global wind patterns cause the surface currents to form in the uppers layer of the ocean. Where these winds blow in the same direction for long periods of time, large currents develop and transport vast amounts of water over long distances.

As these currents flow along the edges of continents, they affect the temperature of the coastal regions. Along the east coast of the U.S., the Gulf Stream carries warm water from the equatorial region to the North Atlantic Ocean, keeping the southeast coast relatively warm. Along the west coast of the U.S., the California Current carries cold water from the polar region southward, keeping the west coast cooler compared to the east coast.

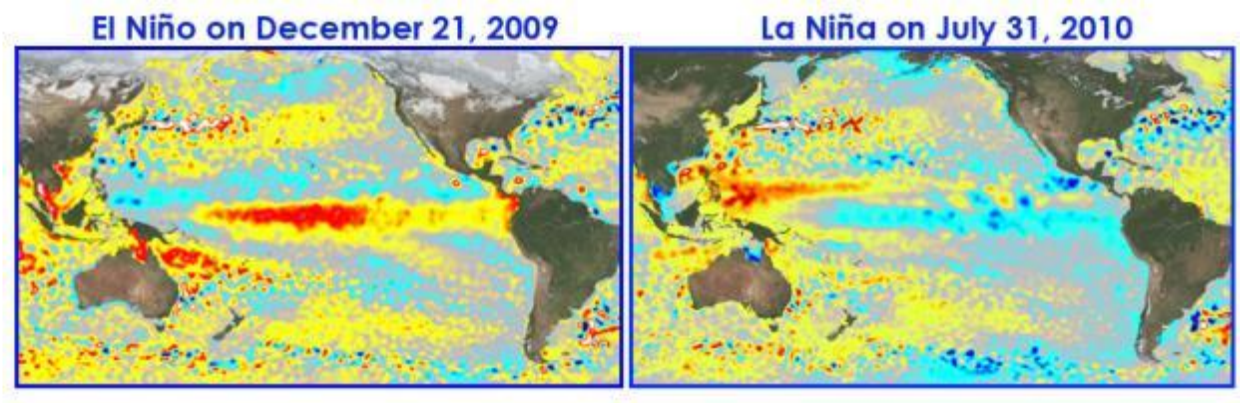
El Niño-Southern Oscillation (ENSO)



During an El Nino Southern Oscillation, the pressure over the eastern and western Pacific changes, causing the trade winds to weaken. This leads to an strong, eastward counter current of warmer waters along the equator.
Map Image Source: Google Earth

The El Niño-Southern Oscillation (ENSO) is a cycle of changing wind and ocean current patterns in the Pacific Ocean. Normally, warmer water is transported westward in the Pacific Ocean by the southeast trade winds until it accumulates near Indonesia. This warm water in the western Pacific Ocean causes low air pressure and high rainfall. (Warmer water causes the air above the ocean's surface to warm and rise, leaving an area of lower pressure. More rainfall is associated with lower air pressure.)

Meanwhile, the eastern Pacific Ocean has high air pressure and less rainfall. Every 3 to 10 years, the southeast trade winds weaken, allowing the warm water to flow further eastward toward South America. Historically, this warmer current of water typically reached the western coast of South America near Christmas and became know to the Peruvian fishermen as El Niño (for the Christ child). El Niño, also known as the warm-water phase of the ENSO, causes the water temperature off of South America to be warmer and prevents the upwelling of nutrient-rich cold water. This event can have devastating effects on marine life, including coral reefs, and fisheries. An El Niño warm-water phase also changes global weather patterns. South America experiences wetter than average weather while North America experiences mild, but stormier winter weather. During an El Niño's, there are fewer and less intense hurricanes in the Atlantic Ocean. Sometimes, after an El Niño subsides, a colder-than-normal water phase, known as La Niña, results.



Red, orange, and white indicate areas where the sea surface height anomalies are higher than normal. Cyan, blue, and violet indicate sea surface height anomalies less than normal. Sea surface is higher when the water is warmer due to thermal expansion. Warm water is less dense and takes up more volume, so the sea surface height is higher.

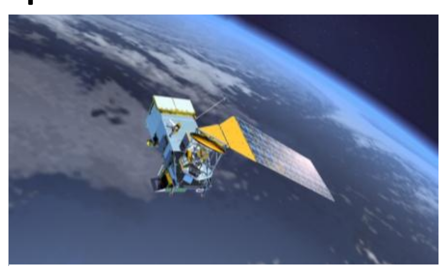
Elevation

Image Credit: Microsoft Clip Art

Air temperature is also affected by the elevation of a location. Temperature normally decreases as elevation or height increases, making locations at higher elevations colder. For every 100-meter increase in elevation, the average temperature decreases by 0.7°C. Even in areas located near the equator, the temperature at higher elevations is cooler.

Methods for Measuring Recent Temperature

You learned that Earth's global mean temperature (GMT) depends on a simple energy balance and that temperature is a measure of the average kinetic energy of the atoms or molecules composing a substance. There are several methods that can be used to determine temperature depending on how far back in time we want to examine.



Artists' concept of National Polar-Orbiting Operational Environmental Satellite System (NPOESS) satellite. Image Credit: NOAA

Earth's global mean temperature (GMT) is determined by averaging measurements of air temperatures over land ocean surface temperatures. Thousands of weather stations spread over land surface worldwide measure the local air temperatures while thousands of ships and buoys measure the local sea surface temperatures. Surface temperature is measured not only by thermometers at ground-based weather stations and on ships, but also by satellites and weather balloons. These measurements are combined so that every square kilometer counts equally toward the global mean temperature. Temperature trends over time are often shown as temperature anomalies. A temperature anomaly is a departure from the long-term average. A positive temperature anomaly means that the temperature was warmer than the long-term average, and a negative temperature anomaly means that the temperature was cooler than the long-term average. Temperature anomalies are useful in analyzing trends.

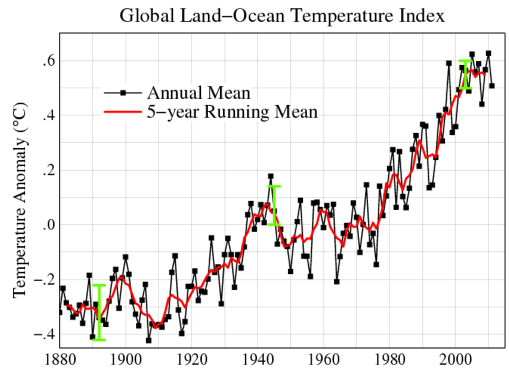


Image Credit: [NASA]

Thermometer records have been kept for the past 150 years over much of Earth. By averaging these records, it is possible to estimate global mean temperature back to the mid-19th century.

Methods for Studying Past Temperatures

How do scientists know what the temperature was beyond 150 years ago? To reconstruct climate history, scientists use proxy data – records used to infer atmospheric properties such as temperature and precipitation. This subfield of climate science is referred to as paleoclimatology. Just like a crime scene investigator solves crimes by examining many different kinds of evidence, a paleoclimatologist can uncover clues about our current and future climate using many sources of proxy data. These sources include historical documents, tree and coral growth rings, deep-sea sediment cores, ice cores, and fossils. Historical documents, such as personal diaries, mariner's logs, records of harvests and quality of wines, can provide indirect indications of past climate. These written documents, however, are not as reliable as the other proxy data sources described below.

Methods of Studying Past Climates			
Method	**Measurement**	**Indicator**	**Time Span**
Thermometers	Temperature	Temperature records at specific locations	Past 150 years
Tree rings	Ring width	Wider tree rings indicates warm weather and more precipitation	Hundreds to thousands of years
Ice cores	Concentration of gases in ice and ocean water	Higher ^{16}O levels indicate a colder climate	Hundreds of thousands of years
Ocean sediments	Concentration of oxygen isotope (^{18}O) in shells of microorganisms	Higher ^{18}O levels indicate a colder climate	Hundreds of thousands to millions of years

The Lost Colony

Analyses of tree ring growth data also help scientists reconstruct past drought records. In the 1580s, the first English colony, known as the Roanoke colony or the Lost Colony, disappeared from the North Carolina coast. Persistent drought in late 16th and early 17th centuries may have contributed to colonists' disappearance.

Image Credit: Wikipedia

Tree Rings and Coral Reefs

Tree rings and coral reefs indicate past growth rates. As a tree grows, it produces a layer of wood beneath the bark. In the spring growing season, the plant tissue produces larger, thin-walled wood cells with a light appearance; and in the summer, the plant tissue produces thick-walled wood cells with a darker appearance. Each tree ring indicates a year of growth. Trees tend to grow faster in warm and moist years.

Some ancient bristlecone pines that grow in the Great Basin region of western North America are approximately 5,000 years old. Generally, tree rings date back 500 to 700 years. In New Zealand, however, the long-lived Kauri pine can help scientists date back as far as 50,000 years.

Scientists obtain coral cores from the largest known coral head on Earth at Ofu Island November 2011. *Image Credit: Dr. Rob Dunbar.*

Many species of corals also have growth rings similar to those of trees. Scientists can extract cores from coral, and the coral growth rings can be used to reconstruct past climate in the tropical and subtropical regions. Corals grow faster in warmer waters.

Ice Cores

Ice cores are cores about 10 cm (4 inches) in diameter that are drilled through kilometers (miles) of ice sheets. An ice sheet is a large thick mass of glacial ice that forms from the accumulation of annual layers of snow. The air between the original snowflakes is trapped as the snow begins to accumulate. As more snow falls, the buried snow is compressed and eventually freezes. Consequently, these "air bubbles" provide a historical record of the gases and even dust particles in the atmosphere at the time the snow fell. The deepest core samples contain the oldest air.

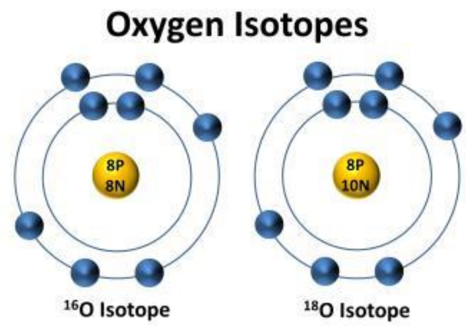
Image Credit: NASA

Ice cores were first extracted from Antarctica and Greenland in 1957-1958, the International Geophysical Year. By the 1990s, the United States and Europe had drilled through the summit of Greenland's ice sheet to the bedrock to obtain about 200,000 years of climate data. And by 2008, the European Project for Ice Coring in Antarctica (EPICA) was able to reconstruct about 800,000 years of climate data. To reconstruct the air temperature from an ice core, scientists analyze the air trapped in the ice using either of two methods – the oxygen isotope ratio or the deuterium to hydrogen ratio.

Isotope Ratios

The Oxygen Isotope Ratio

The oxygen isotope ratio was the first way used to estimate past temperatures from the ice cores. Isotopes are atoms of the same element that have a different number of neutrons. All isotopes of an element have the same number of protons and electrons, but a different number of neutrons in the nucleus. Because isotopes have a different number of neutrons, they have different mass numbers. Oxygen's most common isotope has a mass number of 16 and is written as ^{16}O.



Most of the oxygen in water molecules is composed of 8 protons and 8 neutrons in its nucleus, giving it a mass number (the number of protons and neutrons in an element or isotope) of 16.

The Water (Hydrologic) Cycle

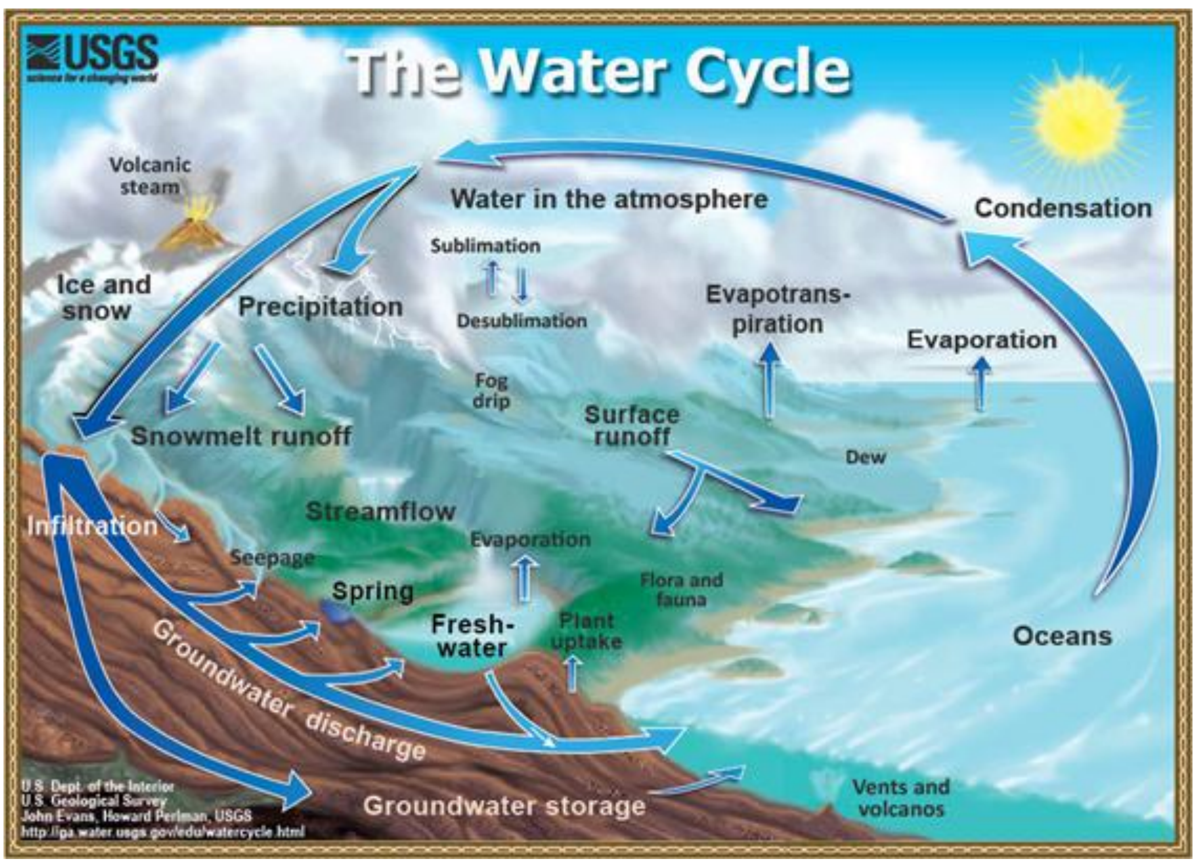
The water or hydrologic cycle is the constant exchange of water in its various forms of liquid, solid (ice and snow), and gas (water vapor) between the earth, the oceans, and the atmosphere. The hydrologic cycle constantly renews Earth's supply of freshwater.

The sun provides energy to drive the system as it heats Earth, causing evaporation of liquid water. Water evaporates from the surface of all the bodies of water on Earth. The water vapor rises with the less dense warm air. Water also evaporates from plants. As plants transport water from their roots, much of the water evaporates through the leaves into the atmosphere. This is called transpiration.

As the air containing water vapor moves farther away from Earth's surface, it cools. Cool air cannot hold as much water vapor as warm air. In cooler air, most of the water vapor condenses into droplets of water that form clouds. The temperature at which water vapor condenses is called the dew point. Clouds form as water vapor condenses on small particles (cloud condensation nuclei) in the atmosphere.

Precipitation falls toward Earth when the water droplets that form in clouds become too heavy to stay in the air. Depending on the temperature of the air near Earth's surface, the precipitation can be in the form of rain, snow, ice, or a combination.

When precipitation reaches Earth, it either evaporates or flows over the surface (known as runoff) where it may accumulate in ponds or lakes or eventually reach streams, rivers, and the ocean. Plants require water and absorb it. Water may also be absorbed into the ground and become groundwater or remain frozen on the surface as snow or ice.



About one out of every 1,000 oxygen atoms contains 2 additional neutrons and is written as ^{18}O.

Depending on the climate, the two types of oxygen (^{16}O and ^{18}O) vary in water. Scientists compare the ratio of the heavy (^{18}O) and light (^{16}O) isotopes in ice cores, sediments, or fossils to reconstruct past climates. They compare this ratio to a standard ratio of oxygen isotopes found in ocean water at a depth of 200 to 500 meters. The ratio of the heavy to light oxygen isotopes is influenced mainly by the processes involved in the water or hydrologic cycle.

More evaporation occurs in warmer regions of the ocean, and water containing the lighter ^{16}O isotope evaporates more quickly than water containing the heavier ^{18}O. Water vapor containing the heavier ^{18}O, however, will condense and precipitate more quickly than water vapor containing the lighter ^{16}O. As water evaporates in warmer regions, it is moved with air by convection toward the polar regions.

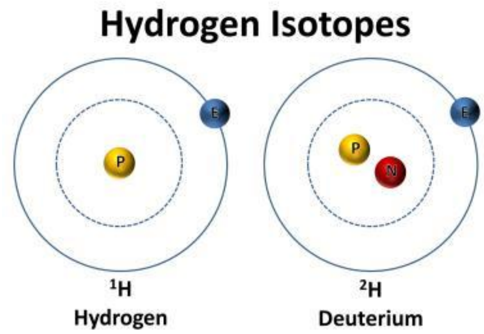
Ocean-floor sediments can also be used to determine past climate. They reflect the oxygen isotope of the ocean water, because the oxygen in the calcium carbonate shells that are deposited on the ocean floor records the oxygen isotope variations in the ocean at the time of formation.

The table explains how the oxygen isotope ratio can be used to reconstruct the type of past climate. The table explains the oxygen isotope ratio for ice cores and ocean water/ocean floor sediments during a colder climate or glacial period.

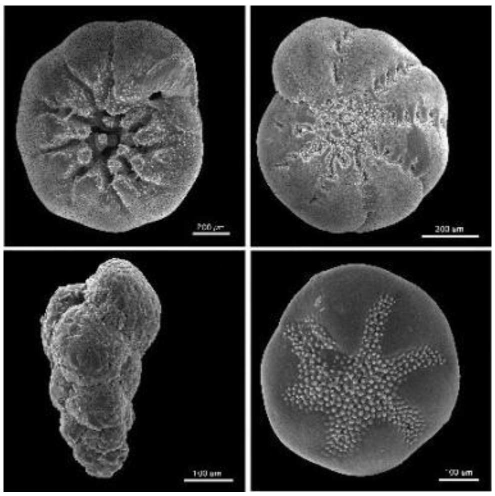
Colder Climates		
	Oxygen Isotopes Ratio	**Explanation**
Ice Core	Ice cores contain more ^{16}O than ocean water, so ice cores have a lower $^{18}O/^{16}O$ ratio than ocean water or ocean-floor sediments.	Water containing the lighter isotope ^{16}O evaporates more readily than ^{18}O in the warmer subtropical regions. As this water vapor (which is enriched with ^{16}O) moves toward the poles, the heavier ^{18}O condenses and precipitates out first at lower latitudes, leaving progressively more ^{16}O in the water vapor reaching the poles. The water vapor that reaches the polar regions precipitates as snow, eventually becoming ice.
Ocean Water/ Sediments	Ocean water and ocean-floor sediments contain more ^{18}O than ice cores, so the ocean water and sediments have a higher $^{18}O/^{16}O$ ratio than ice cores.	When the ocean is colder, it takes more energy to evaporate the heavier isotope, ^{18}O, than it does to evaporate the lighter isotope, ^{16}O. The water vapor with ^{18}O condenses and precipitates out first at lower latitudes. This causes the oceans to have more ^{18}O.

In a warmer climate, ocean water would contain more ^{16}O because as ice sheets melt, the water with ^{16}O is returned to the ocean.

The Deuterium to Hydrogen Ratio



The second way to determine past temperatures is by calculating the deuterium to hydrogen ratio in the ice core samples. The water molecule contains two different isotopes of hydrogen (^{1}H and ^{2}H). ^{1}H contains one proton and no neutrons and ^{2}H, known as deuterium or D, contains one proton and one neutron. The ratio of deuterium to hydrogen in the ice core is compared to the ratio of deuterium to hydrogen in standard mean ocean water. The ice cores contain slightly less of the heavier isotopes of oxygen (^{18}O) and deuterium (^{2}H).


Benthic foraminifera fossils. ***Image Credit: Wikipedia***

Ocean Sediments

The deep ocean floor provides another clue of what was happening in the atmosphere and in the oceans at the time the sediments were deposited. Sediment cores extracted from the ocean floor provide a continuous record of sedimentation dating back many hundreds of thousands of years and even millions of years in certain places. A sediment core from the equatorial eastern Pacific Ocean reveals the climate history as far back as 5 million years.

This analysis is possible because microscopic marine organisms, such as foraminifera, are found in ocean floor sediments. They obtain their oxygen content from seawater to make carbonate shells. You already have learned that the ratio of ^{18}O to ^{16}O is higher in cooler climates. Therefore, the ocean floor sediment cores would contain microscopic shells with more of the heavier oxygen (^{18}O) in a cooler climate.

Temperature Change Over Geologic Time

Human civilization advanced over the past 8,000 years during a relatively constant and favorable climate. However, Earth's climate has not always been so constant and favorable for humans. Global mean temperature (GMT) has been 8° to 15°C warmer than today with polar areas free of ice, and GMT has been 5° to 15°C (40 to 60°F) cooler in mid-latitudes with continental glaciers – some as thick as 1 mile covering areas as far south as New York City.

Nearly two centuries ago, naturalists wondered how large boulders could end up in odd places, like river valleys and plains. They knew that the boulders were too massive to be transported by rivers. Louis Agassiz (1807-1883) was a young professor who studied fossil fish. He proposed that a giant ice sheet once covered large areas of Earth. His classic *Studies on Glaciers*


Milutin Milankovitch. ***Image Credit: Wikipedia***

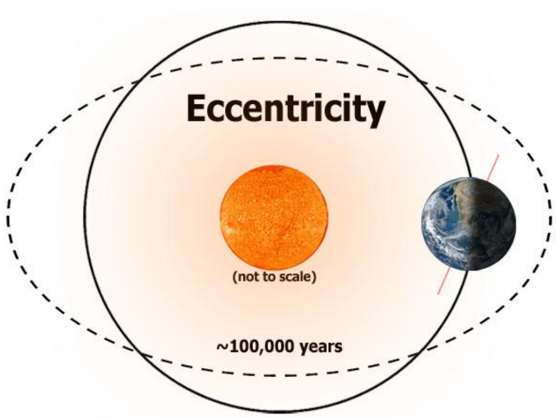

Louis Agassiz. ***Image Credit: Wikipedia***

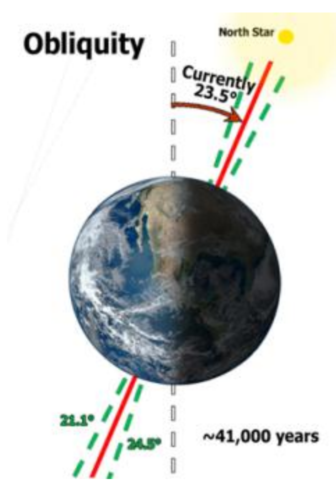
(1840) gave rise to a new field of research.

The Causes of Glaciation

Milutin Milankovitch (1879-1958) was a Serbian mathematician who, for more than 25 years, worked on producing the first numerical estimates of the effect of variations in Earth's orbit on the latitudinal and seasonal variations in solar radiation. Today, his theory is the most widely accepted explanation for the cause of glaciations. The Milankovitch Theory explains the 3 cyclical changes in Earth's orbit and tilt that cause the climate fluctuations occurring over tens of thousands of years to hundreds of thousands of years. These fluctuations include changes in the shape (eccentricity) of Earth's orbit, the tilt (obliquity) of Earth's axis, and the wobbling (precession) of Earth's axis.

First, Earth's orbit can be nearly circular, as it is presently, or more elliptical. This orbital change from circular to more elongated, is known as **eccentricity** and takes about 100,000 years to go from nearly circular to elliptical and back to nearly circular in shape. When the orbit is more circular, as it is now, there is less variation in the distance between the sun and Earth. When the orbit is more elliptical, glaciation is affected by the time of year (season) that Earth is closest to the sun.





The second change is in the tilt of Earth's axis, known as *obliquity*, which varies between 22.1° and 24.5° every 41,000 years. As you have learned, Earth's axis is currently tilted 23.5°. When the tilt is less, the winters are not as cold and the summers are not as warm. Warmer air can hold more water vapor and therefore, produce more snow during the winter months. Because the summers are not as warm, the previous winter's snow does not melt. This promotes glacier formation.

The third change is in Earth's axis. Each 24 hours, Earth rotates once around its imaginary axis. About every 23,000 years, the axis itself also makes a complete circle or *precession*, causing Earth to "wobble." This "wobble," causes Earth to be closer to the sun in July instead of January and intensifies the summer temperatures in the Northern Hemisphere. Because the Northern Hemisphere has more landmasses at higher latitudes where ice sheets can form and grow, the position of this hemisphere is important.

The interplay of these three cyclical changes affects the amount of solar radiation that Earth receives at different latitudes and during different seasons. Currently, we are in a period of relatively small variations in solar radiation, and scientists do not predict a new ice age for 50,000 years.

Climates of the Past

Throughout much of Earth's geologic history, the global mean temperature was between 8°C and 15°C warmer than it is today with polar areas free of ice. These relatively warm periods were interrupted by cooler periods, referred to as ice ages. A decrease in average global temperature of 5°C may be enough start an ice age. The term "ice age" is misleading — an "ice age" is actually a long period of climatic cooling, during which continents have repeated glaciations (glacial periods) interspersed with interglacial periods. During a glacial period, continental ice sheets, polar ice sheets and alpine glaciers are present or expand, sometimes covering as much as 30% of the continental landmasses. During an interglacial period, the climate is warmer and glaciers melt and retreat, and ice may cover less than 10% of Earth's land surfaces. During an ice age, climate fluctuates between glacial periods lasting tens of thousands of years and shorter interglacial periods.

Several ice ages have occurred over Earth's geologic history, and there is evidence of at least five major ice ages over the past 4.6 billion years. The table on the next page shows Earth's generalized climatic history.

During the Precambrian and Paleozoic eras, four major ice ages occurred. The Mesozoic era spans from about 245 to 66 million years ago, and it is often called the "age of the dinosaurs." This era was divided into three periods known as the Triassic, Jurassic, and the Cretaceous periods. During the Mesozoic era, there is no evidence of major glaciation, due in part to the large supercontinent, Pangaea, being located closer to the equatorial region of the planet. Some parts of Pangaea extended toward the South Pole but were still warm. As Pangaea split and the continents moved closer to their current positions, the climate remained warm. About 65 million years ago, there is evidence that a giant asteroid struck Earth.

Era	Period	Epoch	Beginning of Interval	Ice Ages (in blue)
Cenozoic	Quaternary	Holocene or Recent	(10,000 years ago)	Quaternary glaciation (2.75 million years ago to present)
		Pleistocene	1.7 MYA	
	Tertiary	Pliocene		
		Miocene		
		Oligocene		
		Eocene		
		Paleocene	66 MYA	
Mesozoic	Cretaceous			
	Jurassic			
	Triassic		245 MYA	
Paleozoic	Permian			
	Carboniferous			Karoo Ice Age (360 through 260 million years ago)
	Pennsylvanian			
	Mississippian			
	Devonian			
	Silurian			Andea-Saharan (460 through 420 million years ago)
	Ordovician			
	Cambrian		570 MYA	
Precambrian				Cryogenian (850 through 630 million years ago)
				Huronian (2.4 through 2.1 billion years ago)
			4.6 billion years ago	

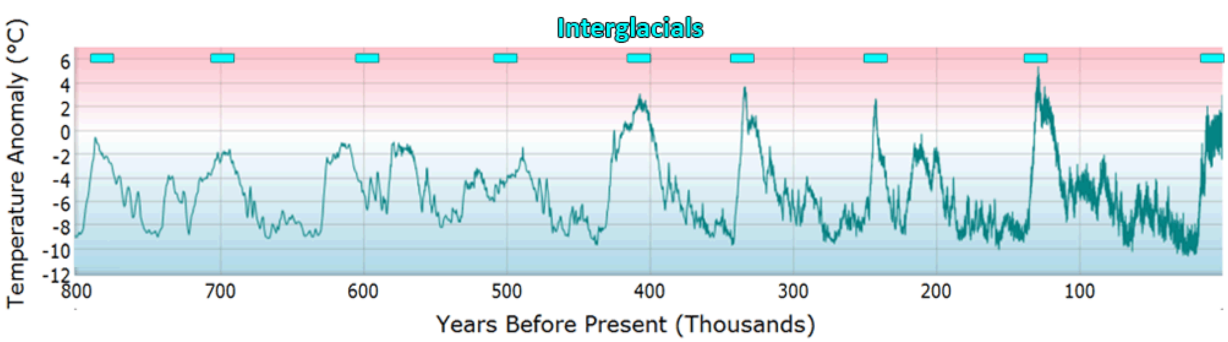
MYA = million years ago

Scientists think that this event caused a mass extinction of the dinosaurs, who had dominated Earth for over 250 millions years, and other life forms.

During the late Paleocene epoch, Earth continued to warm. A huge amount of carbon dioxide flooded the ocean and atmosphere in possibly less than a span of 1,000 years, causing global average temperature to rise 5 to 9°C (9°to 16°F). This event is known as the Paleocene-Eocene Thermal Maximum (PETM). During this time, the ocean warmed and became more acidic. It is still unknown where all the carbon came from, but one idea is that methane hydrates, which are minerals in the ocean floor sediments, became unstable releasing a huge amount of methane into the water and atmosphere. In Module 2, you learned that methane is a major greenhouse gas.

Approximately 55 million years ago, Earth entered a long cooling trend due mostly to a decrease in the concentration of carbon dioxide in the atmosphere. (In Module X, you will learn more about other causes of major shifts in climate.)

The most recent ice age began about 2.75 million years ago. This marked the beginning of the Pleistocene epoch. This epoch is characterized by periods of glaciation and warmer periods or interglacial periods. Overall temperature dropped by 4°C (7.2°F) and Earth entered the glacial/interglacial sequence characteristic of the last 2.75 million years. The following figure shows the sequence of glacial and interglacial periods over the past 800,000 years. Therefore, at the present time, Earth is in an interglacial period within the most recent ice age. Often, when you hear someone refer to the ice age, they are referring to the most recent glacial period within the current ice age that began 2.75 million years ago.



You have probably heard that the planet is experiencing a warming trend, but as you have read, climate has fluctuated many times over Earth's long geologic history. So how do you know if this trend is actually happening and if so, how fast it is warming?

To learn more, proceed to Investigation *How Has Temperature Changed Over Time?*