

Chapter 9 Variations In Earth's Orbit

“At present the globe goes with a shattered constitution in its orbit.... No doubt the simple powers of nature, properly directed by man, would make it healthy and a paradise”

—Henry David Thoreau

The changing seasons are among the most familiar short term climate cycles. The change of summer into fall, or winter into spring illustrates the variability of temperature and the adaptability of Earth's living creatures and plants. The parade of seasons is caused by the tilt in Earth's axis of rotation, an imaginary line drawn through the north and south poles.

Earth spins like a top, completing a revolution every 24 hours, but it is slightly tilted from the plane of its orbit around the Sun. Today, this tilt is 23.5° but, as we shall see, this amount changes over time—referred to as variation in *axial obliquity*. Why Earth tilts like this is a mystery. Some think it might be a result of the collision that formed the moon.

As Earth orbits the Sun, the direction of the tilt remains constant, just like a spinning top. So, during the summer, the tilt in the northern hemisphere is toward the Sun and, during the winter, it points away. The longer summer days allow more sunlight to warm Earth, while shorter, winter days mean less warmth and colder weather. When the northern hemisphere is tilted toward the Sun, the southern hemisphere is tilted away. This causes the seasons to be reversed between the north and south. At the South Pole, winter starts in June.

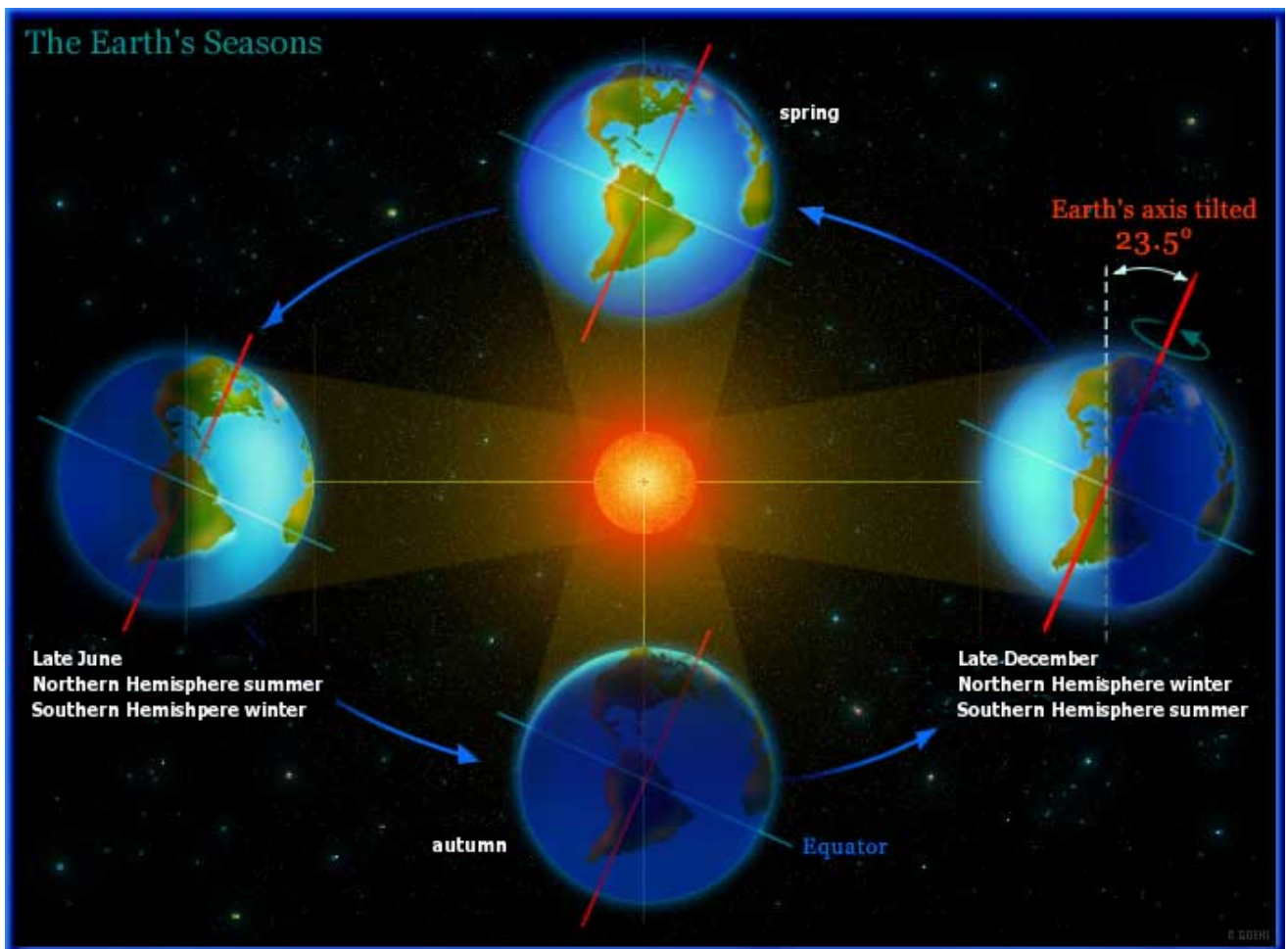


Illustration 104: Earth's seasons due to axial tilt. Source NOAA.

People have long understood what causes the seasons and ancient observers of the night sky noticed other changes as well. Early astronomers noticed that the canopy of stars was slowly moving around Earth, causing the stars of the zodiac to slowly move through the seasons. This is due to a phenomenon known as *precession*. The discovery of precession is usually attributed to the Greek astronomer Hipparchus of Nicaea,[†] in the 2nd century BC. He was the first to develop accurate models of solar and lunar motion.

Reportedly, Hipparchus made use of the observations recorded by the Chaldeans for several centuries preceding his own observations. Virtually all Hipparchus' writings were lost, including his work on precession. We know of it today because Ptolemy mentioned the works of Hipparchus in his *Almagest*. Ptolemy explained precession as the rotation of the celestial sphere around a motionless Earth. It is reasonable to assume that Hipparchus, like Ptolemy, thought of precession in geocentric terms as a motion of the heavens (see page 146).

There has been speculation that other cultures discovered precession prior to Hipparchus. The Babylonians may have known about precession as early as 330 BC. According to al-Battani,[‡] Chaldean astronomers had measured the difference between the solar and sidereal year. The solar year is the length of time that the Sun takes to return to the same position along its path among the stars relative to one of the equinoxes. The sidereal year is the time it takes for the Sun to return to the same position with respect to the stars of the celestial sphere. This is the same length of time as the orbital period of Earth. Because precession causes the equinoxes to move backward along the ecliptic, a solar year is shorter than a sidereal year. The value of precession is the difference between the solar and sidereal years.

Claims have been made that precession was known in Ancient Egypt. Some buildings in the Karnak temple complex were allegedly oriented toward the

point on the horizon where certain stars rose or set at key times of the year. When precession made the orientations inaccurate, the temples would be torn down and rebuilt. Of course, observing precession's effects doesn't mean the Egyptians understood what caused the changes.

The first known reference to precession resulting from the motion of the Earth's axis appears in Copernicus's *De Revolutionibus Orbium Coelestium*, where he called precession the third motion of the Earth. Over a century later it was explained in Newton's *Philosophiae Naturalis Principia Mathematica* to be a consequence of gravitation. Newton's original precession equations contained errors and were later revised by d'Alembert.

Scientists came to suspect that these variations, linked to Earth's travels around the Sun, might have an impact on climate. Establishing the connection between variations in Earth's orbit, attitude and long term climate change took more than 150 years and was an on again, off again affair.

Cycles of Earth

Scientists in the mid 19th century had come to accept Louis Agassiz's Ice Age theory and were casting about for explanations as to why they would occur. In the ninth edition of his *Principles of Geology*, Charles Lyell speculated that variations in Earth's orbit might be the cause, but provided no proof for the conjecture. The first scientist to attempt to prove this link between Earth's orbit and ice ages was a self-educated Scot named James Croll.

James Croll (1821-1890) was one of those people who seem to have been prevalent in the Victorian British Empire, the self-taught amateur scientist who ended up a major contributor to a number of fields of study. Born to a poor rural family, Croll only attended

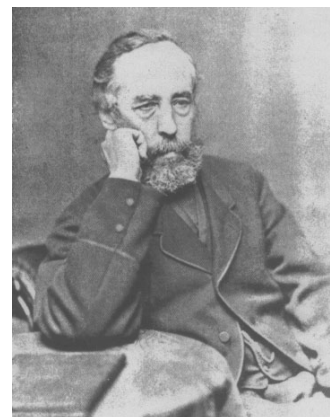


Illustration 105: James Croll, 1821-1890.

[†] Hipparchus (ca. 190 BC-120 BC) Greek astronomer, geographer, and mathematician.

[‡] Muhammad ibn Jabir al-Harrani al-Battani (ca. 853-929) Arab astronomer, astrologer and mathematician.

school until 13 years of age, when he had to quit to help work the family farm. He had a varied career outside of science, working as a hotel manager, an insurance salesman, an itinerant industrial equipment repairman, and other odd jobs. Eventually, he found a position as caretaker at Anderson College in Glasgow, which gave him time to pursue more scientific matters.

Though his first publication was on philosophy, after reading a book by the French scientist Joseph Adh mar on the influence of wobble in Earth's axial tilt and its eccentric orbit on ice ages, Croll became obsessed with climate change. Adh mar claimed that the combined effects of these two factors would result in alternating glacial periods in the northern and southern hemispheres. Some of Adh mar's other claims were a bit wacky, which diminished the impact of the good ideas contained in his book. But, Croll and several others took note and pushed the investigation further. For 25 years, Croll was to be captivated by what he termed "The Fundamental Problem of Geology."

Croll was a very methodical man, with a deep desire to understand the fundamental nature of the problems he studied. His approach to understanding the impact of Earth's orbital eccentricities involved arduous, intricate calculations. Though the elliptical nature of Earth's orbit had first been calculated by Laplace, in 1773, Croll's calculations were much more painstaking.

He published his first paper on the causes of climate change in 1864, and it rocketed him to prominence in geological circles. Ice ages and their causes were a topic of great interest at the time. No one had developed an accurate way to tell when the last glacial period had ended or how long it had lasted. Croll corresponded with Charles Lyell, sending his ideas of links between ice ages and variations in Earth's orbit.

In 1875, Croll published his major work on the linkage between Earth's orbital variations and climate, *Climate and Time in their geological Relations: A Theory of Secular Changes of the Earth's Climate*. In it, he estimated that the last glacial period had ended 80,000 years ago. He also reiterated Adh mar's conjecture that the glaciers

would alternate between the poles in a 11,500 year cycle. Acceptance of Croll's theory was at its peak.

Geologists working in the field began to use glacial drift deposits and erosion to try and date the glacial episodes experimentally. As their data came in, discrepancies with Croll's carefully calculated, but theoretical dates began to arise. The alternation between northern and southern hemispheres was also shown to be erroneous. By the end of the 19th century, Croll's astronomical theory of climate change was discredited and discarded.

The rise and fall of Croll's theory is a good example of how scientific progress is made. Croll built on the works of others, including Agassiz and Adh mar, both of whom he readily acknowledged. His work corrected and refined their theories while making new predictions of its own. Other scientists, trying to confirm or disprove Croll's predictions, showed the astronomical theory to be incorrect in several ways, leading to its fall from favor. But sometimes, the basic idea behind a theory is correct, even if its expression is flawed. In this case, the fundamental ideas were correct—Croll's theory would rise again.

The scientist who revived Croll's theory was Milutin Milankovitch, a Serb mathematician and engineer whose initial fame was due to concrete. Born in 1879, in the town of Dalj on the Danube, he was well-educated during his youth. He attended university in Vienna, eventually earning his PhD in engineering. His dissertation was on the uses of reinforced concrete in buildings, and provided a wealth of data about strengths and shapes used for construction.

With his detailed knowledge of concrete, Milankovitch quickly found work with a large engineering firm in Vienna, eventually becoming head engineer. He earned notoriety designing

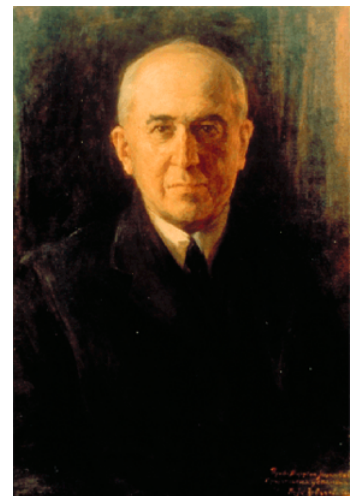


Illustration 106: Milutin Milankovitch

buildings all across Europe, and his career seemed on a steady course. But the political storm clouds, that would eventually lead to World War I, were starting to gather.

Though he loved his work and life in Vienna, in 1908, political tensions led him back to Serbia. He became a professor at the University of Belgrade, giving up his much higher paying job as an engineer. Milankovitch was a man driven to succeed at whatever he worked on, and he was soon looking around for problems where he could apply his considerable mathematical skills. After reading Croll's work on orbital variation and climate, Milankovitch decided to investigate the causes of climate change.

A great deal of scientific progress had been made since Croll's work. Better measurements of planetary movements were available, along with better historical climate data. Milankovitch was not trying to explain ice ages, but all climate changes. He was seeking a mathematical theory that would give the temperature for any point on Earth's surface at any given time. In fact, he would eventually extend his calculations to the Moon and Mars.

Though his work was interrupted by WWI, during which he was briefly imprisoned, by 1920 he published *A Mathematical Theory of the Thermal Phenomenon Produced by Solar Radiation*. His book generated interest among meteorologists, but gained little notice from geologists of the time.

The German meteorologist Wladimir Köppen was one of the scientists who took note of Milankovitch's theoretical approach to climate. Köppen's daughter was married to geophysicist Alfred Wegener. Wegener is the scientist who first put forth a serious theory of continental drift, which we investigated in Chapter 8. Milankovitch began a collaboration with Köppen and Wegener that was to last their lifetimes. When Köppen and Wegener published *Die Klimate die Geologischen Vorzeit* (Climates of the Geological Past), in 1924, it helped to bolster Milankovitch's work.

Among the key contributions of Milankovitch's work were the ideas that different latitudes experienced the impact of orbital variation

differently, and that the key to the onset of glaciation is cool summer weather, not colder winters as had previously been assumed. Understanding that there were a number of factors involved in regulating climate, Milankovitch didn't try to give absolute temperature values. Instead, he used "equivalent latitude." If a location's equivalent latitude decreased, effectively moving the climate south, temperatures were warmer. Similarly, an increase in equivalent latitude meant temperatures were colder.

Once again, Europe was preparing for war when Milankovitch decided to publish his definitive book on climate, *Cannon of Insolation and the Ice Age Problem*, printed in German in 1941. For a time, this resurgent theory of climate change found wide acceptance, but it was not to last.

New dating techniques and geological data began to uncover discrepancies in Milankovitch's predictions. Around the time of his death, in 1957, Milankovitch's theory was out of favor for much the same reasons as Croll's. History was repeating itself.

Milankovitch had managed to out-live the Nazis and the second World War, only to find himself trapped in the dismal reality of Communist Yugoslavia. Fortunately, his international reputation as a scientist garnered him some respect from the new regime, allowing him to live out his days in relative peace. But the story doesn't end here.

In the 1960s, several advances were made in geophysics that improved the collection of data about Earth's past climate. Analysis of radioactive isotopes of hydrogen and oxygen, along with the ability of scientists to collect sediment cores from deep ocean beds, greatly improved knowledge of ice age climate changes. In 1970, Wally Broecker and J. van Donk published a paper that detailed temperature changes going back 400,000 years.

In this paper, a number of the apparent discrepancies in Milankovitch's theory were resolved. Though he didn't live to see his theory vindicated, Milankovitch's astronomical theory of climate change is now recognized as the best explanation of the cycles of glacial-interglacial

change. In his honor, these periodic changes in Earth's orbital orientation are called the Milankovitch Cycles.

The Croll-Milankovitch Cycles

Though scientists had long considered the variation in insolation warming from the Sun too weak to cause the waxing and waning of ice ages, the cycles found by Croll, and expanded on by Milankovitch, fit the climate data so well some form of link had to exist. Unlike atmospheric carbon dioxide, where several Earth-bound explanations exist for changing CO₂ levels, there is no way that terrestrial forces can cause the changes in Earth's orbit.

Today, we know variations in the intensity and timing of heat from the Sun are the most likely

cause of glacial/interglacial cycles. This solar variability is partially driven by changes in the Sun's output, but is affected more strongly by variations in Earth's orbit.

There are three major components of Earth's orbit about the Sun that contribute to changes in our climate. These are, in order of longest to shortest cycle, *Orbital Eccentricity*, *Axial Obliquity*, and *Precession of the Equinoxes*. These three variations are shown in Illustration 107.

Earth's orbit goes from measurably elliptical to nearly circular in a cycle that takes around 100,000 years. Presently, Earth is in a period of low eccentricity, about 3%. This causes a seasonal change in solar energy of 7%. The difference between summer and winter is a 7% difference in the energy a hemisphere receives from the Sun.

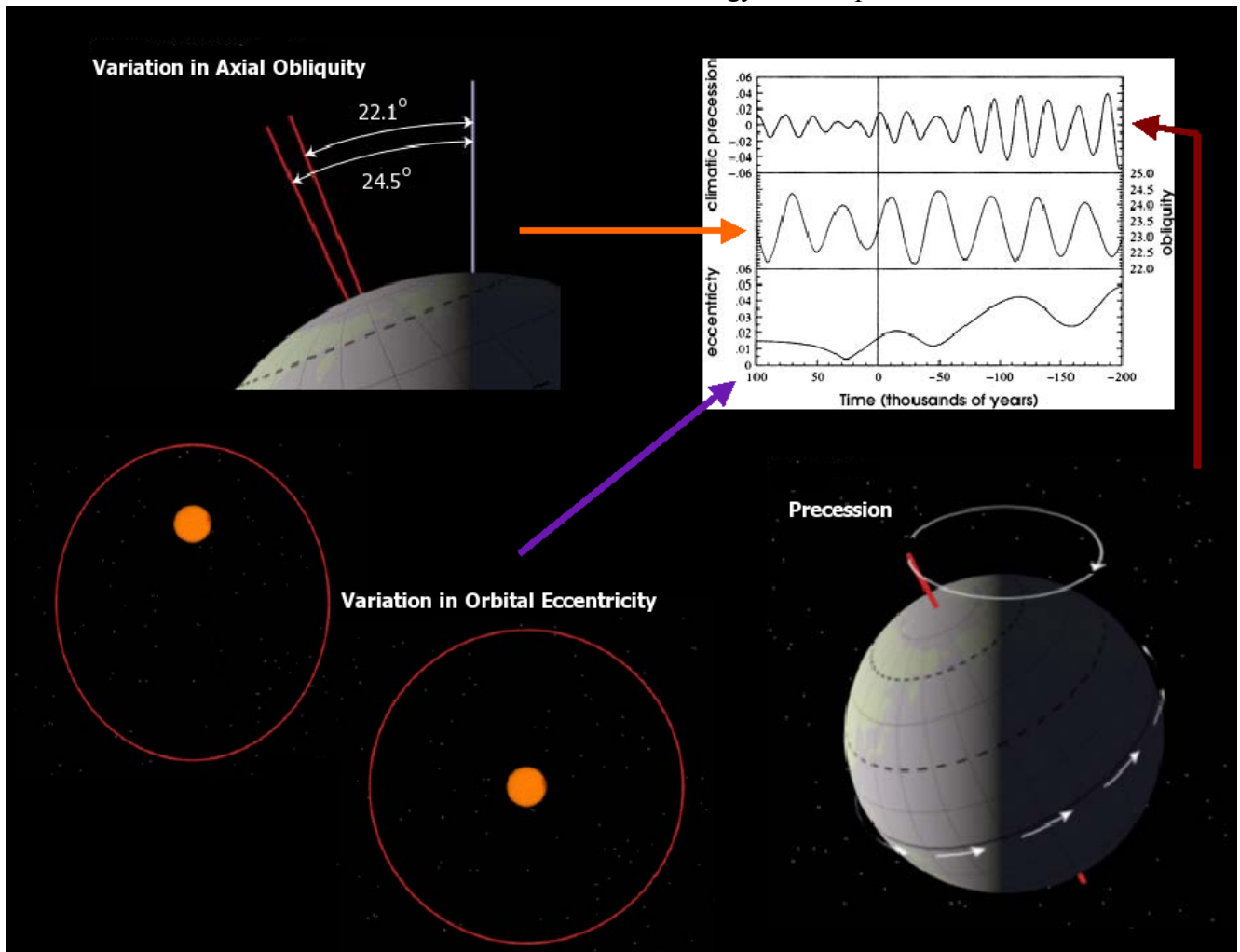


Illustration 107: Variation in Axial Obliquity, Orbital Eccentricity, and Polar Precession. Images from NOAA.

When Earth's orbital eccentricity is at its peak (~9%), seasonal variation reaches 20-30%. Additionally, a more eccentric orbit will change the length of seasons in each hemisphere by changing the length of time between the vernal and autumnal equinoxes.

The variation in eccentricity doesn't change regularly over time, like a sine wave. This is because Earth's orbit is affected by the gravitational attraction of the other planets in the solar system. There are two major cycles; one every 100,000 years and a weaker one every 413,000 years.²⁴⁷

The second Milankovitch cycle involves changes in obliquity, or tilt, of Earth's axis. Presently Earth's tilt is 23.5°, but the 41,000 year cycle varies from 22.1° to 24.5°. This tilt is depicted in the upper-left panel of Illustration 107. The smaller the tilt, the less seasonal variation there is between summer and winter at middle and high latitudes.

For small tilt angles, the winters tend to be milder and the summers cooler. Cool summer temperatures are thought more important than cold winters, for the growth of continental ice sheets. This implies that smaller tilt angles lead to more glaciation.

The third cycle is due to precession of the spin axis. As a result of a wobble in Earth's spin, the orientation of Earth in relation to its orbital position changes. This occurs because Earth, as it spins, bulges slightly at its equator. The equator is not in the same plane as the orbits of Earth and other objects in the solar system. This is shown in Illustration 108.

The gravitational attraction of the Sun and the Moon on Earth's equatorial bulge tries to pull Earth's spin axis into perpendicular alignment with Earth's orbital plane. Earth's rotation is counter-clockwise; gravitational forces make Earth's spin axis move clockwise in a circle around its orbit axis. This phenomenon is called precession of the equinoxes because, over time, this backward rotation causes the seasons to shift.

The full cycle of equinox precession takes 25,800 years to complete. Presently, Earth is closest to the Sun in January and farther away in July. Due to

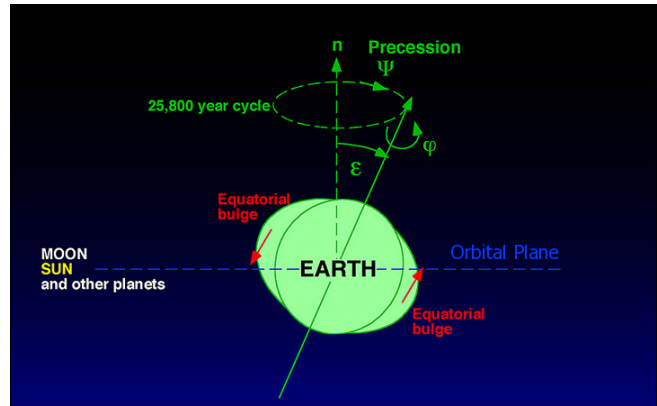


Illustration 108: Precession of Earth's axis of rotation.

precession, the reverse will be true 12,900 years from now. The Northern Hemisphere will experience summer in December and winter in June. The North Star will no longer be Polaris because the axis of Earth's rotation will be pointing at the star Vega instead (see Illustration 109).

A consequence related to this phenomenon is that the Moon is slowly becoming more distant from Earth. The Moon is departing from us at the rate of 1.5 inches (3.8 cm) each year. The idea of the Moon retreating proposed over a century ago by English mathematician and geophysicist George Howard Darwin, Charles Darwin's son, has been

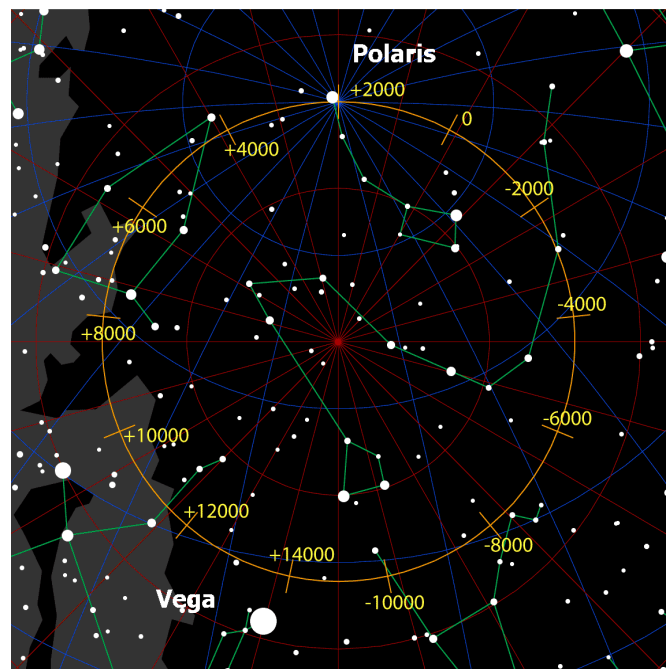


Illustration 109: Path of the north celestial pole among the stars due to precession. Original image by Tau'olunga.

confirmed by measuring the distance to the Moon with lasers.^{248,249}

The tidal drag caused by the Moon's gravity slows Earth's rotation and accelerates the Moon. One of the counter intuitive things about physics is that, if you speed up an object in orbit, it takes longer to complete a full orbital revolution. In orbit, you slow down if you speed up, at least when viewed from Earth's surface. This means that both days and months are getting longer.

This mechanism has been working for 4.5 billion years, since Earth and Moon first formed. There is evidence in the geologic record that Earth rotated faster and that the Moon was closer to Earth in the distant past. We know from silt deposits that, 620 million years ago, a day was 21.9 hours long, there were 13 months/year and 400 solar days/year.²⁵⁰

Tidal forces are also why the Moon always keeps the same side facing Earth. One day, Earth will reach a similar state—a day will be as long as a month. A month will be longer than it is today because the Moon will be farther away, and Earth will show only one face to the Moon. But this shouldn't be a major concern: There is good reason to believe that the Sun will expire, taking Earth and its Moon with it, long before this happens (see Chapter 10).

Cycles Summarized

Individually, each of the three cycles affect insolation patterns. When taken together, they can partially cancel or reinforce each other in complicated ways. Illustration 110 shows how the three cycles combine to affect solar forcing over the past 200,000 years. It is the complex pattern of insolation change created by the interaction of all three factors that caused so much confusion verifying Croll and Milankovitch's predictions.

Adhémar based his predictions on the mathematics of d'Alembert, who calculated precession in 1754. Alexander von Humboldt discredited this theory by pointing out that, though the seasonal insolation varied, the total energy received remained constant. Precession alone was not enough.

Croll used both eccentricity and precession, as well as the effects of glaciation and changing air

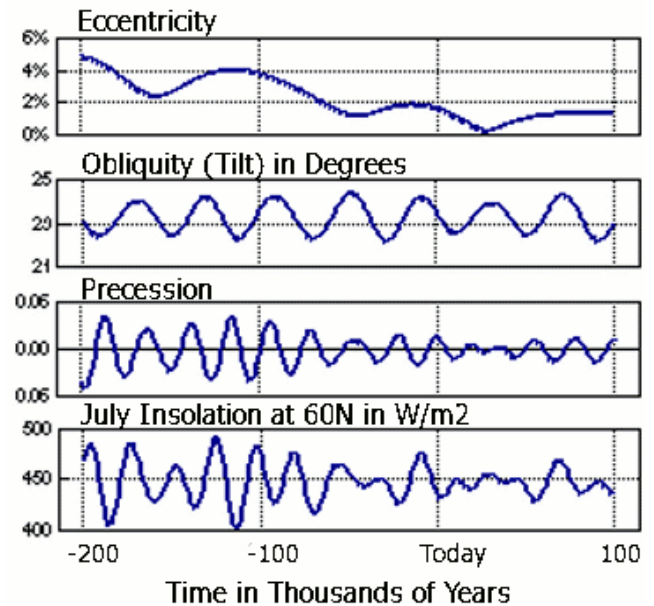


Illustration 110: Relationship of cycles with insolation.
Source NOAA.

currents. In 1875, he added tilt to his calculations. Even then, his interpretation of the factors was not totally correct. Not until Milankovitch produced integrated curves combining all the orbital elements were the cycles on firm footing. But the apparent disagreement with experimental data still caused the theory to fall into disrepute.

Only after work by Erickson, Broecker, et al,²⁵¹ in the 1950s, was the theory revisited. In 1978, Berger corrected the theory with more accurate formulae for calculating insolation variations.²⁵² Today, we use numerical integration to calculate the effects of all the bodies of the Solar System. This is difficult, requiring minimization of the error in present observational data and running long calculations on supercomputers.²⁵³ Croll and Milankovitch had to do their calculations by hand. Science is often a long and tortuous process.

Today, it is widely accepted that Milankovitch cycles are the forcing that decides the timing of glacial/interglacial periods. Data from the glaciation record are in strong agreement with this theory. In particular, during the last 800,000 years, the dominant period of glacial-interglacial oscillation has been 100,000 years, which corresponds to changes in Earth's eccentricity and orbital inclination.

Glacial periods can be triggered when tilt is small, eccentricity is large, and perihelion, when Earth is closest to Sun, occurs during the Northern Hemisphere's winter. Perihelion during the Northern Hemisphere winter results in milder winters but cooler summers, conditions that keep snow from melting over the summer.

Deglaciation is triggered when perihelion occurs in Northern Hemisphere summer and Earth's tilt is near its maximum. There are other factors which act to enhance the forcing effects of the cycles. These include various feedback mechanisms such as snow and ice increasing Earth's albedo, changes in ocean circulation and enhanced greenhouse heating due to increased CO₂ and water vapor concentrations. Earth's current place in the three cycles are as follows:

- **Eccentricity.** Earth's current orbital eccentricity is 0.0167, which is relatively circular. Presently, Earth's distance from the Sun at perihelion, on January 3rd, is 95 million miles (153 million km). Earth's distance from the Sun at aphelion, on July 4th, is 98 million miles (158 million km). This difference between the aphelion and perihelion causes Earth to receive 7% more solar radiation in January than in July. Currently, Earth's orbital eccentricity is close to the minimum of its cycle.
- **Obliquity.** Currently, axial tilt is approximately 23.45 degrees, reduced from 24.50 degrees just a thousand years ago. Even so, Earth's current tilt is almost at its maximum. This explains the contrast in Earth's seasons. A lower degree tilt would result in cooler summers and warmer winters, thus, moderating global temperatures. Some argue that this would cause growth in ice sheets in the high latitudes. Snow would accumulate over the winter and would be less prone to melting and recession during the summer.

- **Precession.** The variation in the direction of Earth's axial tilt is thought to be the most important influence of climate. Today, Earth is closest to the Sun during Northern Hemisphere winter and farthest away during Northern Hemisphere summer.

So currently, Earth's orbit meets only one of the three conditions which lead to the onset of glaciation, Perihelion during Northern Hemisphere winter. As stated above, glacial maximums have occurred roughly every 100,000 years for the past 800,000 years with the last glacial maximum occurring 18,000 years ago. After each glacial period there has been a period of rapid warming. These warming periods are followed by a relatively slow cooling trend leading to the next glacial maximum. Today, we are poised to enter another glacial period but, there are still uncertainties.

The European Project for Ice Coring in Antarctica (EPICA) team has noticed the interglacial period of 400,000 years ago closely matches our own because the shape of Earth's orbit was the same then as it is now. That warm spell lasted 28,000 years so we might not be as close to the next glacial episode as often thought.

Limits of Orbital Forcing

To sum up, scientists believe the Croll-Milankovitch cycles caused the onset of the Holocene interglacial period in the following way. At the beginning of the Holocene, around 15,000 years ago, variation in Earth's orbit and attitude caused a small increase in the solar radiation received from the Sun. Those changes also resulted in a redistribution of solar energy within Earth's atmosphere and ocean, which caused a slight warming, ending the glacial period. Retreating glaciers, melting snow cover, and diminished sea ice exposed larger areas of land and open ocean. The exposed areas absorbed more solar radiation, reinforcing the warming trend. This accelerated warming of the ocean, releasing of large amounts of CO₂ and further reinforcing the warming trend. Temperatures increased to modern levels and have stayed there since—though, the climate continues to undergo variations on century and decade long

time scales. How long the warm period will last cannot be predicted.

Today, scientists believe that the principal cause of glaciations is the intensification of the hydrologic cycle caused by Earth's orbital cycles. Variation in insolation patterns cause tropical oceans to warm, increasing the equator-to-pole temperature gradient. This leads to the growth of land-based ice in high latitudes. In other words, increased heating of the oceans is needed to start a glacial period.

This argument was first made by John Tyndall, the Irish physicist, naturalist and educator, in the late 1800s.²⁵⁴ Greater solar radiation in winter and spring at the expense of summer and autumn, leads to higher frequency of El Niño anomalies. From studying the start of the previous glacial period, similarities can be seen in current orbital changes.²⁵⁵

Although the current variations are less extreme, researchers have concluded, “association of recent positive seasonal anomalies of global mean temperature with El Niño events suggests that the ongoing global warming may have a significant, orbitally influenced natural component. The warming could continue even without an increase of greenhouse gases.”²⁵⁶

Even if there is a connection to current global warming, the Croll-Milankovitch cycles do not explain short term, decadal variations, or the longer term changes that signal the beginning and end of ice ages. We need to look for other influences—in particular, the Sun.