

Milankovitch cycles

The Milankovitch idea—July sun at 65° N

The Milankovitch theory⁽²²¹⁻²²⁵⁾ holds that changes in the orientation of Earth's rotation axis and its orbital shape fix the timing of the glaciations by changing the distribution of sunlight on Earth. The most important Milankovitch parameter is the amount of sunlight during the summer (July) at 65° N latitude. This is crucial, because if it is not warm enough in July, ice cover may grow. If it is warm enough, ice cover can recede. In this way, Milankovitch imagined that the rather small orbital effects could be amplified.

Solar system dynamics

Interestingly, there have been many instances of correlations between Moon phases and weather that have never been understood, and of course, correlation does not imply causation. In the course of tracking the daily variations in temperature measured from a satellite, it was found that the phase of the moon accounts for a global variation in temperature of about 0.02 to 0.03 °C. While this is not high, it is rather amazing that such an effect was seen.⁽²²⁶⁾ While the mechanism is not fully understood, it seems connected with atmospheric Rossby wave motion.⁽²²⁶⁾ At any rate, there is other independent evidence that Earth's position in the solar system can affect temperature.

The *eccentricity*, which indicates how elliptical Earth's orbit is, changes in a 105,000 year cycle. The Earth's eccentricity is now 0.017, and it varies between 0.005 and 0.06.⁽²²²⁾ The greater the eccentricity, the more pronounced the effects of the other changes.

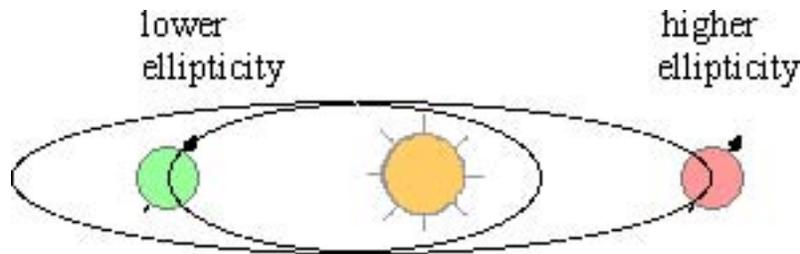


Fig. E16.7.1 The ellipticity of the orbit determines how much sunlight varies due to position in the orbit; in low-ellipticity orbits, there is not much difference at different times of the year, while at high-ellipticity, there is a substantial difference. This parameter is involved in the 100 and 400 kyr cycles. The eccentricity change is highly exaggerated; it changes remarkably little for Earth. ⁽²²⁷⁾

The axial tilt or *obliquity*, now 23.5° , changes from 22.1° to 24.5° with a period of 41,000 years. There are indications of a 42,000 year cycle in fossil pollen from old lakebeds. ^(224,228) The rise and fall of very large lakes leaves sedimentary evidence of past climates. An analysis covering 40 million years ⁽²²⁹⁾ found a 44,000 year cycle corresponding to tilt (as well as 25,000, 100,000, 133,000, and 400,000 year cycles). Increasing the tilt causes colder winters and hotter summers. Current winters are slightly milder than mean conditions. ⁽²²²⁾

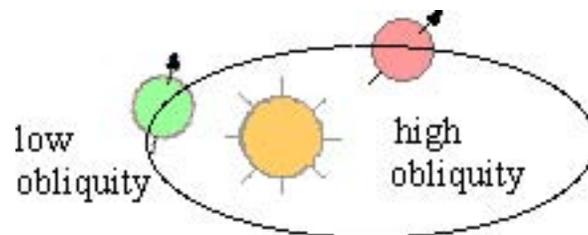


Fig. E16.7.2 The obliquity measures the axial tilt of Earth. The obliquity is currently 23° , relatively high. This makes a stark difference between summer and winter insolation. There is a much reduced difference at low obliquity. The obliquity changes in a 41 kyr cycle. ⁽²²⁷⁾

Earth's rotation axis precesses (changes direction) with respect to the fixed stars with a period of 21,000 years. (This is known as the *precession* of the equinoxes and is the reason for the "Ages" of the Zodiac—we are now about to enter the Age of Aquarius.) This precessional change, or "wobble," is important because it fixes the points on the

orbit at which summer and winter occur. The Northern Hemisphere's winter now occurs near Earth's closest approach to the Sun, moderating its severity. At midlatitudes, this effect is equivalent to a change of 10% in intercepted sunlight.⁽²³⁰⁾

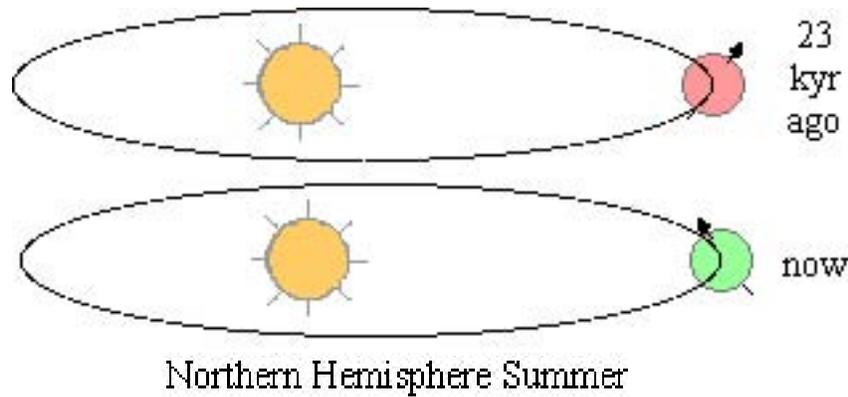


Fig. E16.7.3 The axial precession changes the direction Earth's tilt points. Now it points in the direction of Polaris (that is our "North star." Twenty-three thousand years ago, it pointed at an opposite point in the sky, and twenty-three thousand years from now, it will point there again.⁽²²⁷⁾

The 100,000 year cycle should not cause the variations observed if the couplings are linear, since the eccentricity should merely in that case change the size of the precession effects. The eccentricity changes are also rather small, as the orbit of Earth is remarkably circular even at its greatest eccentricity.

In 1976, a study based on use of two deep-sea cores to measure $\delta^{18}\text{O}$ (which together represent 468,000 years of history), showed the existence of periodic signals of 105,000, 41,000, 23,000, and 19,000 years.⁽²²⁴⁾ (See **Extension 16.3, Proxy measurements** for more information on $\delta^{18}\text{O}$.) The 100,000 year cycle, which was supposed just to modulate the others, was the *major* feature of the climate record; it explained 50% of the observed variance. The 40,000 year cycle explained another 25% of the observed variance, with 10% explained by the 23,000 year cycle. The work of Hays, Imbrie, and Shackleton established the existence of the approximate 100,000 cycle in sea sediment cores,^(224,231) and many later workers have seen this cycle as well.^(224,229,232)

A breakthrough in understanding came in 1980, when the Imbries⁽²³¹⁾ showed that a very simple model caused sufficient nonlinearity to give a good simulation to the data. They chose to look at polar ice sheets, because that is the only obvious part of the climate system for which response times are anywhere near those from the orbital driving forces. Ice in glaciers takes more time to accrete than to melt, which introduces delays into the interactions.⁽²³¹⁾

There is a lag of $9,000 \pm 3,000$ years between the orbital input and the 41,000 year component of the response. In their fine-tuned simple model (with only four parameters describing the eccentricity, obliquity, precession, and time delays), the Imbries found a warming time delay of 10,600 years and a cooling time delay of 42,500 years. Thus, computer models seem to be verifying Milankovitch's guess. For example, they suggest that ocean feedbacks cause cooling at high northern latitudes, and more moisture being transported from the Equator to the poles through the air, amplifying the effects.⁽²³³⁾ While there has been much work done since that time, it generally finds agreement (see the section below on possible disagreements).

Supporting evidence

It is now generally agreed that the orbital effect is the primary cause of glacial-interglacial changes in an ice age climate because of development of recent evidence supporting the theory.^(122,125,228) Models also seem consistent with observation.⁽²³⁴⁾ On the twenty-fifth anniversary of the publication of Ref. 224, Crowley commented that any initial "skepticism faded as evidence for a widespread imprint of orbital cycles in the geologic record mounted."⁽²³⁵⁾ He goes on to write: "In the 25 years since the publication of [Ref. 224], the importance of Milankovitch cycles has penetrated many areas of

paleoclimatology. ... These data, and some classic land sections ... have helped scientists to stitch together a near-continuous orbital-scale chronology for the past ~40 million years, allowing much more precise timing of important evolutionary and extinction events and better estimates of the timing and rate of climate change.”⁽²³⁵⁾

As one example, the Milankovitch theory predicts a glacial episode to occur in 4000 to 5000 years, reasonably consistent with the past history of Earth.^(236,237) Heinrich events, in which huge volumes of ice enter the Atlantic and drop debris, appear to be correlated with the precession parameter.⁽²³⁸⁾ The Asian summer monsoon is sensitive to obliquity and precession periods.⁽²³⁹⁾

A 23,000 year cycle was found in the deposit of carbonaceous sediment (the remains of plankton) in the Pacific,⁽²²⁵⁾ in cave calcite,^(125,126) in corals⁽¹²²⁾—everywhere (see **Extension 16.1, ENSO events** and **Extension 16.3, Proxy measurements** for a discussion of how coral can tell time and temperature). Plankton should be more numerous when the Sun shines more and less numerous when the Sun shines less. Hence, the density of plankton skeletons is greater when more sunlight is available, and this is detected in sediment.

Studies of coral terraces indicate high sea levels 80,000, 105,000, and 125,000 years ago, combinations of eccentricity and obliquity effects.⁽²²⁴⁾ An apparent contradiction in the timing of a glaciation 127,000 years ago was resolved using uranium-dating of reef levels from Henderson Island, which found complete agreement with Milankovitch.⁽²⁴⁰⁾

A five million year record from Lake Baikal of silica-bearing sediments using multiple proxies for climate shows evidence of the 41,000 year cycle throughout the record, but particularly strongly 1.8 to 0.8 million years BP. The 23,000 year cycle has been

strongest during the past 400,000 years. The data also show that the 100,000 year cycle has been strong only during the last 800,000 years. The record also showed major cooling episodes around 1.7 and 2.7 million years BP.⁽²⁴¹⁾ An analysis of a ten million year record found similar results.⁽²⁴²⁾ Similarly, a 65 million year record shows that the Milankovitch cycles' effects are quite varied—the 100,000 year cycle is very pronounced sometimes, and not large at others, but the data always show the effects.⁽²⁴³⁾

Shakleton (Ref. 243) made an analysis of the presence of oxygen-18 trapped in small bubbles in the ice from 400,000-year-long ice core record taken at Vostok station. The amount of oxygen-218 in air does not depend on temperature, as does the amount of oxygen-18 in ocean water, but does depend on the amount of ice locked up in icecaps. He also studied the oxygen-18 amounts in bottom-mud dwelling foraminifera, which depends both on the volume of world ice and the water temperature. See **Extension 16.3, Proxy measurements** for more information on $\delta^{18}\text{O}$.

The deeper the location of the fossil in the core, the older it must be. As a result, a record of time and ice cover is determined. Shakleton was able to find the interesting result that the amount of ice was less important than the amount of carbon dioxide and that the pattern followed a 100,000 year cycle.⁽²⁴⁴⁾

An interesting event 23 million years ago was the coincidence of a period of low eccentricity (associated with a cool climate by itself) and small variability in obliquity (which also causes cooling by itself). Earth was thus exposed to low seasonal variations and smaller-than-normal extremes of warm and cold. This event was captured by examination of a 5.5 million year record from deep sea cores. The record is examined using two proxies, the oxygen-18 measurements from shells of foraminifera and carbon-

13 measurements (see **Extension 16.3, Proxy measurements** for more information on $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$).

In this case of the 5.5 million year record examined in Ref. 245, both strands of data led to observation of a strong 400,000 year cycle. The strong 100,000 year cycle and the usual shorter cycles were identified.⁽²⁴⁵⁾ In this coincidence 23 million years ago, a short glaciation occurred that led to sea floor erosion that determines the Oligocene-Miocene boundary.

The Antarctic ice sheets waxed and waned in synchrony with Milankovitch. Data from sediments from shallow cores in the western Ross Sea show that eccentricity and obliquity determined the way the ice margins changed.⁽²⁴⁶⁾ So the southern ice sheet behaved around 25 million years ago just as the Quaternary Northern Hemisphere ice sheets did about 2.5 million years ago. And the 15 million year history of the cores show the continuation of the synchrony over an extended time.⁽²⁴⁶⁾

The spectacular long records^(241-243,246) that show continuous response to the Milankovitch mechanism and the existence of evidence that all over Earth ice adjusted over millions of years in the same way seems to be overwhelming corroborative evidence for its validity. Most scientists are convinced that the mechanisms will eventually all be understood because the preponderance of evidence is so great.

Another triumph of the revived Milankovitch theory was a prediction that the timing attributed to paleomagnetic boundaries were off by several thousand years. Argon-argon dating supported the orbital predictions.⁽²³⁵⁾

Origin of the 100,000 year cycle

Despite Crowley's optimistic view,⁽²³⁵⁾ conceptual problems still exist, as he himself admits. Why did ice ages begin suddenly again 65 million years ago? Why does the Imbrie model give too low a power to the 100,000 year cycle and too much to a 400,000 year cycle compared to observation, which seems not to find much 400,000-year signal (although Ref. 245 did observe a strong signal)? Why did the strong effects of obliquity and precession provoke such a weak response, while to weak 100,000 year cycle provokes such a strong response?

Some guesses have been advanced that in addition to the ice sheet extent, there may be a resonance due to the fact that bedrock subsides under the weight of ice sheets and rises when the sheets vanish (*isostatic uplift*). If there is a 10,000 year response time, the 100,000 year cycle, ten times as long, will be enhanced.⁽²²²⁾ The oceans could lock into a 100,000-year cycle somehow.⁽²⁴⁷⁾ The 100,000 year oscillation of Earth's passage through the ecliptic (the plane containing the orbits of the planets; Earth's orbit is very slightly tipped to the ecliptic and the tipping varies, with 200,000 years needed to complete a cycle).⁽²⁴⁸⁾ None of these possible explanations seems particularly convincing.

An intriguing answer may be that the 100,000 year response mixes with the 400,000 year response in a frequency modulation effect (similar to sidebands in radio waves). J. A. Rial suggested that modulation of the 100,000 year cycle by the 400,000 year cycle gives rise to the observed variability of the duration of the ice ages as well as the lack of a clear signal of the 400,000 year effect.⁽²⁴⁹⁾

Between 3 and 1 million years BP, there was a regular flip-flopping of glaciation at the obliquity rhythm, 41,000 years. Paillard investigated two simple phenomenological models in which the system could be altered from a steady state by fixed rules involving thresholds, and found quite startling agreement with the situation observed during that time, including the 100,000 year cycle.⁽²⁵⁰⁾ This dynamic oscillation may play a role in reality, but it seems to need more theoretical grounding.

Possible confounding evidence and gaps in knowledge

Examination of data from a lake in Hungary from 2.6 to 3.05 million years BP do not show the Milankovitch timing at all, but rather shorter cycles.⁽²⁵¹⁾ It is unclear how these “sub-Milankovitch” cycles could be accommodated in the model.

The phase shift found in a study of the Asian monsoon, and the fact that there are different phase changes for the precession and obliquity data, seems to indicate there is a problem in our understanding of the Milankovitch mechanism. The physics of the situation has no easy explanation. This is an area ripe for more understanding.

One problem that seemed very puzzling, and possibly fatal for the Milankovitch mechanism was raised by measurements of timing of glaciation from a place called Devil’s Hole, a Nevada cave.⁽²⁵²⁾ The timing of the glaciation end “Termination II” seemed incompatible with Milankovitch—the shift to interglacial values of $\delta^{18}\text{O}$ was complete by 142,000 years ago ($\pm 3,000$ years), while Termination II occurred 127,000 years ago ($\pm 6,000$ years). But the insolation couldn’t have triggered the end of the glaciation by this time. It appeared that the event preceded the cause, which would be fatal for a scientific theory. Other suggestions of problems were found that seemed to be in agreement with the Devil’s Hole results—indications of warming from Papua-New

Guinea 142,000 years ago; higher sea levels apparently seen 132,000 years ago (the other data were consistent with both, but seemed to support the Devil's Hole challenge).⁽²⁵³⁾

A further monkey wrench was tossed into the gears when Edwards, Cheng, Murrell, and Goldstein reexamined both the Barbados coral used to time Milankovich originally and the Devil's Hole calcite crystals and found both to be correct!⁽²⁵⁴⁾ That seems not to make sense, the data appear to be too contradictory. It just seems unbelievable.

So things stood until another result showed how these data could agree.⁽²⁵⁵⁾ Herbert et al. examined the oceanic warming and cooling off California using $\delta^{18}\text{O}$ as the proxy for time and ice volume on several long cores (the sediment accretes at about 80 μm per year).⁽²⁵⁵⁾ They showed that where the California Current affects the land, the land warmed 10,000 to 15,000 years prior to deglaciation because California Current sea surface temperatures warmed. The sea surface temperatures in regions away from California were unaffected by warming until the full-scale deglaciation occurred.⁽²⁵⁵⁾ Apparently, wind systems shifted prior to the full-scale warming and affected the California Current.⁽²⁵⁵⁾ This is the reason that the Devil's Hole results showed warming prior to the onset of full-scale deglaciation—it was in a region that was a harbinger of what was to come.

Research on past frequency contributions to climate changes in the tropics identify as important the 19 to 23 kyr (precession, or wobble), the 41 kyr (obliquity, or tilt, which should not much affect the tropics), and 100 kyr (ellipticity) cycles,⁽²⁵⁶⁾ while at higher latitudes the 41 kyr cycle is most pronounced.⁽²⁵⁷⁾ Liu and Herbert examined sea surface temperature records spanning almost 2 million years for the eastern Pacific Ocean.⁽²⁵⁸⁾ They looked at alkenones found in marine sediments (see **Extension 16.3, Proxy measurements**), and were able to construct a tentative past history of changes. They

found a strong connection between the 41 kyr cycle in the tropics and global ice volume as inferred from the $^{18}\text{O}/^{16}\text{O}$ ratio before about 1 million years ago. However, this is surprising because the ice sheets were relatively small at that time. There is a strong connection to the insolation at high latitudes that Liu and Herbert take to mean that “climate variability at our study site must have been determined by high-latitude processes that were driven by orbital obliquity forcing” in the early Pleistocene.⁽²⁵⁸⁾ Hall et al. find similarly that in addition to Milankovich one needs atmospheric dynamics to explain northern hemispheric winter responses to insolation (summer is satisfactorily explained without the atmospheric dynamics).⁽²⁵⁹⁾

At the beginning of the millennium, it seems that the Milankovitch mechanism, which predicts the onset of glaciations from the amount of July sunshine at 65° N latitude, is in good shape. While certain questions remain, the orbital ellipticity, obliquity, and precession clearly have influenced glaciation timing and severity.