# Milankovitch Theory as a Mechanism for Cenozoic Climate Oscillations

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*Writer's Comment: On the first day of Geology 108, I was a little worried knowing that the assigned research paper would be much more scientific than anything I'd written before. Fortunately, the paper could cover any desired topic relating to paleoclimates. I decided to research Milankovitch Cycles, which I briefly learned about in another geology course. This was a chance to investigate their role in shaping Earth's climate and to assess whether the theory associated with them (MilankovitchTheory) is a valid explanation for the climate oscillations seen over the last 65 million years, known as the Cenozoic Era. I hope this paper might encourage those beginning to write more technical or scientific works. It's a big step, but you'll likely find that you're capable of much more than you realized. I'd like to thank Professor Spero for all the help during the quarter and my TA, Babs Wortham, for providing helpful feedback while I worked on this assignment.*

*Instructor's Comment: What do Jupiter, Saturn and Barbados have in common? They all play a role in our understanding of how Earth's climate system has varied over geologic timescales. Veronica has written a wonderful synthesis for the GEL 108 (Paleoclimates) writing requirement that describes how researchers have searched for data to test the theory of the early 20th century Serbian mathematician, Milutin Milankovitch. In brief, Milankovitch proposed that changes in the Earth's orbit around the sun have varied due to the effect of the gravitational attraction of the planets. Changes in Earth's eccentricity (elliptical orbit), obliquity (tilt) and precession* *(direction axis leans) alter the amount of sunlight striking the Earth on timescales ranging from 20,000 to 400,000 years and control how much heat the northern hemisphere continents see during summers. As summers warm or cool, snow accumulation and continental glaciers shrink or grow and ocean sea level falls or rises. Coral reefs growing during these time periods such as the uplifted reefs found on Barbados in the Caribbean, record the changing sea level in their growth position and skeletal chemistry. Using such mathematical and geological features, researchers have managed to explain the broad controls on Earth's climate over millions of years of geological time. Veronica has followed her passion for math and geology and captured some of the paths that paleoclimate researchers had to follow in their attempts to apply the scientific method to unravel the Milankovitch controls on Earth's climate system. I congratulate her on this writing project.*

*—Howard J. Spero, Department of Earth and Planetary Sciences*

In 1941, Milutin Milankovitch published *The Canon*, a book containing calculations he made to arrive at his proposed cause of Earth's ice ages. The hypothesis, now called Milankovitch Theory, relies on three "astronomical elements" (see Fig. 1): eccentricity, the shape of Earth's orbit around the sun; obliquity, Earth's axial tilt; and precession, the direction at which Earth leans (Grubic 2006). Each element varies periodically, on the orders of 100, 41, and 23 and 19 kyr respectively (Berger 1988). Following the conclusions of Wladimir Köppen, who linked the changes in Earth's insolation to established climate records, Milankovitch theorized that summer insolation in the northern hemisphere was influenced by the cycles of the three

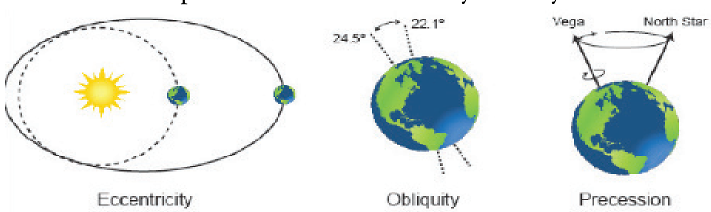


*Figure 1. The three astronomical elements, or Milankovitch Cycles, discussed in Milankovitch Theory. "Geologic Time,"* Time Scavengers.

astronomical elements, also called Milankovitch Cycles, triggering the ice ages (Grubic 2006).

Milankovitch Theory is worth examining as a potential explanation for the ice ages. If correct, the timing of past glaciations can be determined; this follows from Milankovitch's insolation curve (see Fig. 2), a "preliminary Ice Age calendar" constructed using the periods of the three astronomical elements (Grubic 2006). It measures variations in summer insolation at latitudes of 65°N over the last 600 kyr, reflecting his theory that cool summers in the northern hemisphere are required to prevent the melting of polar ice (Berger 1988). Since 1941, researchers have examined climate records to find evidence which either supports or refutes the theory, most importantly regarding past glaciations. Some records show a correlation between summer insolation and ice sheet growth (Kawamura et al. 2007), while others present contradictory information, such as incorrectly predicted timing of deglaciations (Winograd et al. 1992). However, the works of other researchers suggest that Milankovitch Theory correctly explains other forms of climate change (Broecker et al. 1968; Kutzbach and Street-Perrott 1985; Zachos et al. 2001). Thus, northern hemisphere summer insolation can be attributed to some Cenozoic climate change, but not to all of the last four glacial terminations.

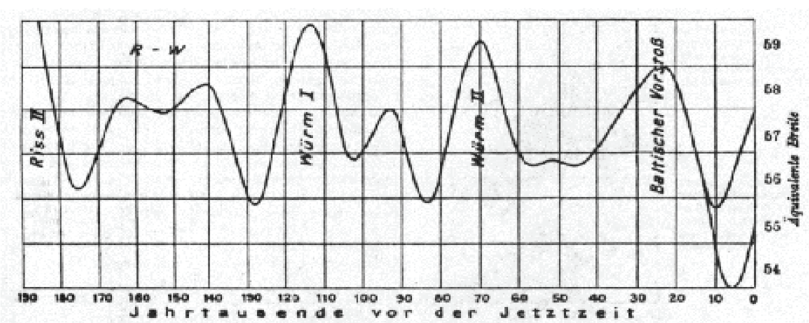


*Figure 2. The Milankovitch Curve, showing changes in radiation over the last 190 kyr. The graph displayed here is a reproduction of the Milankovitch Curve from the book* Die Klimate der geologischen Vorzeit. *Laurence Hecht, "The Coming (or Present) Ice Age: A Long-Term Perspective on the Current Global Warming Fad," 1993-1994.*

To visualize this mechanism, consider a series of experiments conducted by Kutzbach and Street-Perrott (1985). Using the National Center for Atmospheric Research's Community Climate Model, climates during January and July from 18 to 0 ka were simulated at intervals of 3 kyr. The experiment focused on lake-area variations in the northern tropics from 8.9-26.6°N latitude. Beginning at 15 ka, an increase in northern summer radiation led to increased precipitation and, therefore, lake area. The boundary conditions for polar ice were not considered a major factor after additional simulations for 9 ka, one with an ice sheet and one without, produced nearly identical results. Because their findings agreed with the geologic record, Kutzbach and Street-Perrott proposed that northern summer insolation caused variations in northern tropical lake levels since 18 ka, with the boundary conditions of high-latitude glaciation having negligible influence (Kutzbach and Street-Perrott 1985).

The experiment shows a physical feature, lake area, responding to changes in summer insolation in a way that agrees with Milankovitch Theory. While not physical evidence of climate change, the simulation's conclusions are valuable because of their consistency with the geologic record. Reconstructing paleoclimates in this way showed that summer insolation should be investigated further as a potential source of climate change, but it cannot confirm that it is a source without physical evidence.

One such record of climate change is the Barbadian coral reefs, which were analyzed by Broecker et al. (1968). Although the oldest rocks in Barbados are overlain by a thick coral cap, the coral's topography largely reflects that of the sediment, so it was used to determine changes in sea level and when they occurred. Their work involved radiometrically dating coral samples from three major terraces by analyzing for the isotope $^{230}$Th, giving ages of about 82, 103, and 122 kyr respectively, which coincide with oceanic high stands. These figures agreed with those obtained using a second method, which instead analyzes for $^{231}$Pa, validating their results. A modified Milankovitch curve, showing changes in summer insolation at 45°N rather than 65°N, revealed that the warm peaks they arrived at closely corresponded to those at 82, 106, and 127 ka, as predicted by the curve. They attribute these primarily to the obliquity and precession cycles and conclude that the data from the coral cap supports Milankovitch Theory (Broecker et al. 1968). Thus, their work gives evidence for variations in northern summer insolation causing climate oscillations since 122 ka (Broecker et al. 1968). However, Broecker et al. do not explicitly suggest climatic change from eccentricity, the other Milankovitch Cycle. To find such evidence, it is necessary to examine climate records that span a longer time.

The work of Zachos et al. (2001), for instance, explores the effect of eccentricity on climate change over the course of 5.5 myr. They examined a benthic foraminiferal record spanning the Oligocene-Miocene boundary, a time when Antarctica lacked permanent ice. After collecting isotope records from the foraminifera, they found that spectral power, a measure of isotope variance, was concentrated at all Milankovitch bands, including every eccentricity frequency band of 95, 125, and 406 kyr. In fact, the $\delta^{18}O$ record strongly correlated with these eccentricity bands, at least from 21.0 to 23.4 Ma. Observing similar $\delta^{18}O$ oscillations for both planktonic and benthic foraminifera, they suspected that Antarctica experienced infrequent glaciations, with higher $\delta^{18}O$ values, a result of cooler temperatures, signifying more ice. They believe cool summers are necessary for polar ice to expand. Zachos et al. also noted a climate anomaly that occurred at the Oligocene-Miocene boundary, a time marked by both minimal eccentricity and "low-amplitude variability in obliquity," or an obliquity node. This pairing is thought to have led to cool polar summers and, therefore, Antarctic glaciation. They propose that, at the boundary, reorganization of either the ocean or atmosphere system was amplified by the carbon cycle, which then "enhanced" climate change from the anomaly. The gradual rise in $\delta^{13}C$ before the boundary reflects such a change in the carbon cycle, supporting their hypothesis (Zachos et al. 2001).

In brief, Broecker et al. and Zachos et al. both discuss physical evidence supporting Milankovitch Theory. The ages of the coral samples determined by the former agree with the warm peaks of the Milankovitch insolation curve, and the isotope record constructed by the latter corresponds with the eccentricity cycle. Together, all three Milankovitch Cycles are held accountable for some form of climate change. Broecker et al.'s conclusion that cool northern summers are essential for polar glaciation is consistent with that of Kutzbach and Street-Perrott about their climate simulation. It would seem that Milankovitch Theory could explain Earth's ice ages, such as the last four Antarctic terminations, which are transitions from glacial to interglacial periods.

Other researchers, however, disagree. It is important to address these conflicting results because the validity of the theory is called into question. First, consider a report by Kawamura et al. (2007), which suggests that the timing of "the last four deglaciations" agrees with Milankovitch Theory. Their tuning method, which lacks the uncertainties of earlier methods, measures the ratio of $O_2$ and $N_2$ in the air trapped in Antarctic ice cores. This provides the age of the ice and was applied to both Dome Fuji and the Vostok core. Because the two timelines agreed within 1 kyr, they used this method to find a correlation between Antarctic climate and Milankovitch Cycles. Kawamura et al. found that variations in the Dome Fuji $\delta^{18}O$ and site temperature records coincided with the precession frequency bands of the Milankovitch curve. Furthermore, their chronology reveals the timing of atmospheric $CO_2$ increase during Antarctic terminations. The $CO_2$ and temperature records indicate that the last four terminations occurred at a time of increasing northern summer insolation. With these findings, they concluded that northern summer insolation determines Antarctic climate change (Kawamura et al. 2007). While their research uses the terminations to support Milankovitch Theory, other reports suggest that at least one of the terminations cannot be explained by this mechanism (Winograd et al. 1992; Gallup et al. 2002).

One of these reports shows inconsistency between the experimentally-determined timing of the Antarctic terminations and the timing predicted by Milankovitch Theory. In their research, Winograd et al. (1992) studied a layer of vein calcite at Devils Hole, Nevada by extracting an ice core called DH-11. They determined that this pure calcite "precipitated continuously" since 500 ka because there was no evidence of recrystallization or gaps in the record. After collecting samples from DH-11 and analyzing for $^{18}O$, they constructed a plot of $\delta^{18}O$ over time, which matched the "sawtooth pattern" found in marine $\delta^{18}O$ records. Their results also generally agreed with the "well-established" SPECMAP $\delta^{18}O$ and Vostok deuterium records, which use different materials and dating methods. Some disagreements do exist, such as two features apparent in the DH-11 record but missing from SPECMAP, but these features are found in other "equally detailed" records, suggesting that DH-11 is indeed a reliable climate record (Winograd et al. 1992).

Following this, Winograd et al. (1992) showed the disagreement between their data and Milankovitch Theory. The discrepancy lies with Terminations II and III, the second and third most recent Antarctic terminations. According to the DH-11 record, "[t]he warming associated" with these terminations preceded the peaks in northern summer insolation. Using independently-measured sea level variations, they determined that the sea level rise associated with Termination II began around 145-150 ka, which agrees with the age 150 ka shown in the DH-11 record. Thus, Termination II did not coincide with the insolation maximum that occurred at about 128 ka. Termination III also conflicted with the theory, as the associated temperature rise took place at a time of only average insolation. Given these points, they concluded that glacial cycles were not the result of changes in northern summer insolation, but instead in "the atmosphere-ice sheet-ocean system" (Winograd et al. 1992).

The final source presents a similar inconsistency with the timing of Termination II. The research by Gallup et al. (2002) focuses on a site in Barbados "in the last interglacial terrace," with the fastest uplift rate found on the island. For these reasons, it is an ideal location for finding coral reefs from Termination II. Gallup et al. used $^{230}Th$ and $^{231}Pa$ dating to determine the ages of several coral samples, allowing for the construction of a sea level record. To ensure accuracy, three criteria were considered for the samples, including agreement between the $^{230}Th$ and $^{231}Pa$ ages and absence of signs of recrystallization. Upon dating the samples, they found that most of the sea level rise associated with Termination II occurred before 135 ka. Although some samples gave different ages despite meeting all the criteria, they are attributed to other isotopic events. This means that sea level, which was approximately 18 meters below its present value, was within 20% of the maximum sea level of the last interglacial period by 135 ka, contrary to Milankovitch Theory. However, they believe it is possible that insolation played a role in the deglaciation even if it did not directly force it, as could have isostasy, or equilibrium of the Earth's crust, from the presence of the ice (Gallup et al. 2002).

These two reports use different climate records to come to the same conclusion: the timing of at least one of the Antarctic terminations, determined by their research, is different from the predictions of Milankovitch Theory. Winograd et al.'s use of the DH-11 record showed that neither the sea level rise of Termination II nor the temperature rise of Termination III occurred during maximum northern summer insolation. Similarly, the timing of the Termination II sea level rise found by Gallup et al. disagreed with the theory. Although it is still possible that Terminations I and IV resulted from increased summer insolation, as Kawamura et al. showed, their research suggested that *all four* of these terminations agreed with Milankovitch Theory. Thus, there is a question of why the reports conflict with each other.

In finding the answer, notice that even when measures are taken to produce accurate results, disagreements are still found between and within climate records. The most notable cases are the two records conflicting with Milankovitch Theory. The DH-11 record was tested for accuracy by comparing it to the SPECMAP and Vostok deuterium records, and although there was resemblance, some features were only present in a separate record (Winograd et al. 1992). Alternatively, inconsistencies existed within the Barbadian coral reef record analyzed by Gallup et al. Most samples dated Termination II back to 135 ka, but others meeting the specified criteria still gave different figures (Gallup et al. 2002). This is not to discredit research which conflicts with the theory, nor to say that the implications of research supporting it are necessarily correct. Even though the research done by Kawamura et al. (2007) supported Milankovitch Theory as an explanation for the last four glacial terminations, this clearly diverges from the others. Take, for instance, the timing of Termination II, which Kawamura et al. agree occurred around 138 ka. This is close to the age of 135 ka that Gallup et al. arrived at, but the latter used sea level records to show that this figure was inconsistent with the theory, whereas the $\delta^{18}O$, $CO_2$, and site temperature records used by the former suggested otherwise.

This is not an issue of how each group of researchers made their conclusions, but with the procedures taken. Gallup et al.'s work showed that when setting regulations for the data obtained, inconsistent data can still be found. These were attributed to other events, but the fact that mismatched information was found at all indicates that their method could not disregard irrelevant data itself; it was strong, but not perfect. In addition, Winograd et al.'s research did not agree with past reports, suggesting inaccuracy with either their procedure or procedures of earlier research. Newer methods, like the one used by Kawamura et al., may produce more accurate results because of reduced uncertainties. However, until their results are duplicated, the older reports cannot be dismissed; thus, Milankovitch Theory cannot be attributed to Terminations II and III at this time.

As can be seen, paleoclimate research over the last 50 years has supplied evidence both supporting and refuting Milankovitch Theory as the mechanism for climate change throughout the Cenozoic. Various reports find the theory to be a valid explanation for occurrences like oceanic high stands and the $\delta^{18}O$ oscillations recorded by benthic foraminifera, since the timing of these records agree with the timing of northern summer insolation and Milankovitch Cycles (Broecker et al. 1968; Zachos et al. 2001). Insolation is especially important since it is thought to influence the conditions in which polar glaciation occurs (Berger 1988). This was apparent in the research by Kawamura et al. (2007), where the last four glacial terminations appeared to have occurred at times of increasing northern summer insolation. Equally important are those reports highlighting the dependence of other features, like sea level and lake area, on insolation (Broecker et al. 1968; Kutzbach and Street-Perrott 1985). Collectively, these reports provide evidence of Milankovitch Cycles and northern summer insolation having a combined effect on global climate, but there are also reports which disagree. As discussed, the contradicting results of research done on the last four Antarctic terminations could be because of inaccurate methods used by these researchers or in the earlier records. As techniques improve, future research on the timing of the terminations will likely yield results agreeing with one or more of these records. Milankovitch Theory as an explanation for the terminations depends on these results. It would be ideal to find alternative climate records and compare them to previously established records, or to revisit older records with updated dating methods.

Finally, it is time to assess if Milankovitch Theory is indeed the cause of Cenozoic climate oscillations. Several of the examined reports favor this view, but some proposed other factors that could be accountable. Gallup et al. (2002) suggest that isostasy determined Termination II, with insolation playing a small role. Change in the atmosphere or ocean system was also discussed as a potential factor by both Zachos et al. and Winograd et al., albeit for events millions of years apart. The separation suggests that global climate has potentially been affected by these systems since at least the Oligocene-Miocene boundary, so this factor must be considered when assessing climate change, in addition to those suggested by Gallup et al. What stands out most of all, though, is the variety and multitude of sources supporting both Milankovitch Cycles and northern summer insolation as forces of Cenozoic climate change. Therefore, Milankovitch Theory must explain at least some of the climate oscillations of the Cenozoic. Isostacy and the atmosphere and ocean systems may have influenced some of the oscillations, but Milankovitch's proposed mechanism appears to be responsible for most of the change. However, the theory cannot yet be accounted for Terminations II and III until more research, using methods with fewer uncertainties than previous ones, is performed. It is worth determining the primary cause of Earth's glacial terminations because if Milankovitch Theory is the answer, paleoclimates can be reconstructed not just for the Cenozoic, but further back in geologic time. In any case, scientists will have a better understanding of the forces influencing global climate. With this understanding of Earth's past, humanity can better understand its own contribution to global climate, facilitating change in our daily lives that will help secure the Earth's future.

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