Climate Change Science

Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bengaluru

Lecture 32
Milankovitch Theory

In the previous lecture, the onset of ice ages was attributed to variations in Earth's orbital parameters, originally hypothesized by Milutin Milankovitch over a century ago. He proposed that changes in Earth's orbit around the Sun significantly altered seasonal and latitudinal distribution of solar radiation, particularly in the polar regions, which influenced the buildup or melting of snow and ice. However, his hypothesis was not initially accepted, primarily due to two reasons. First, there was a lack of empirical data on the timing and frequency of past ice ages. Ice core records, which now provide such information, only became available in the last 60 years. Second, contemporaries of Milankovitch underestimated the effect of small changes in radiation, believing they were insufficient to initiate large-scale ice melt.

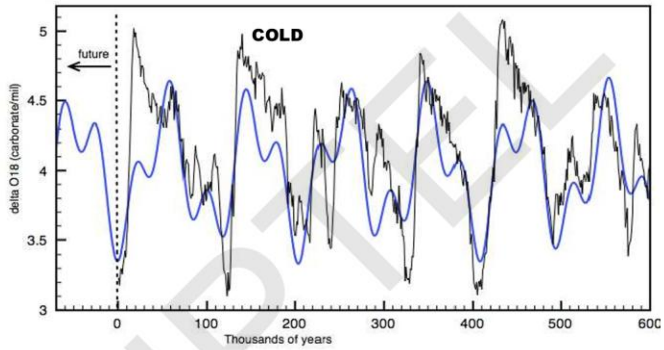
Critics at the time were unaware of the role of climate feedback mechanisms, which can amplify small initial changes. For instance, water vapor acts as a positive feedback: more insolation in the polar regions leads to snowmelt, increasing atmospheric moisture, which in turn enhances the greenhouse effect and causes further warming. Cloud feedbacks and surface albedo changes (as snow and ice reflect more sunlight than open ground or water) also contribute significantly to amplifying the climate response. When these feedbacks are considered, Milankovitch's calculations which showed variations in polar summer insolation of around 30–40 W/m^2 become more convincing.

Milankovitch focused on three key orbital elements:

1. Obliquity (axial tilt), varying over 41,000 years,
2. Precession (the wobble of Earth's rotational axis), with a ~23,000-year cycle,
3. Eccentricity (shape of Earth's orbit), which changes on a ~100,000-year timescale.

He emphasized obliquity and precession as the dominant factors, because they directly affect seasonal insolation at high latitudes. However, when Vostok ice core data revealed a strong 100,000-year periodicity in glacial cycles, the focus shifted to eccentricity. This seemed contradictory, as eccentricity causes only minor variations in total annual global radiation. Milankovitch addressed this by pointing out that eccentricity modulates the impact of precession. Precession only alters seasonal insolation when eccentricity is non-zero. Hence, the combined effect of precession and eccentricity significantly impacts summer insolation at high latitudes, particularly in the Northern Hemisphere.

Importantly, Milankovitch asserted that it is summer insolation, not winter, that controls ice sheet melting, since polar regions receive no sunlight in winter. Therefore, stronger summer insolation over extended periods is necessary to terminate glaciations. Today, with improved paleoclimate data and climate modeling capabilities, Milankovitch's theory is broadly validated and remains central to our understanding of glacial-interglacial cycles.

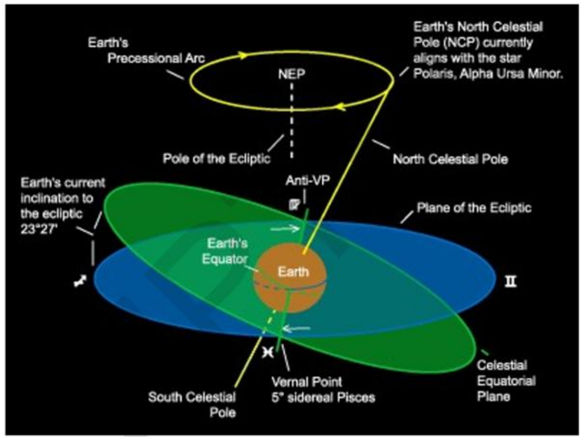


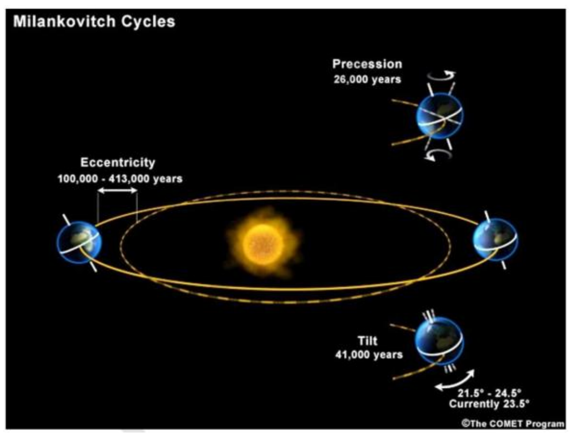
δO_{18} record from microfossils in the ocean. Blue line solar radiation at 65° N

The above figure containing data timeseries for the last 600,000 years shows a black curve representing the oxygen-18 isotope concentration from calcium carbonate in deep ocean sediment cores (not ice cores), which serves as a proxy for past global temperatures. Alongside it, a blue line indicates the incoming solar radiation at 65° North latitude, a representative location for the Northern Hemisphere polar region. This latitude is particularly important because Milankovitch identified it as a key zone where summer insolation critically affects the formation and melting of ice sheets.

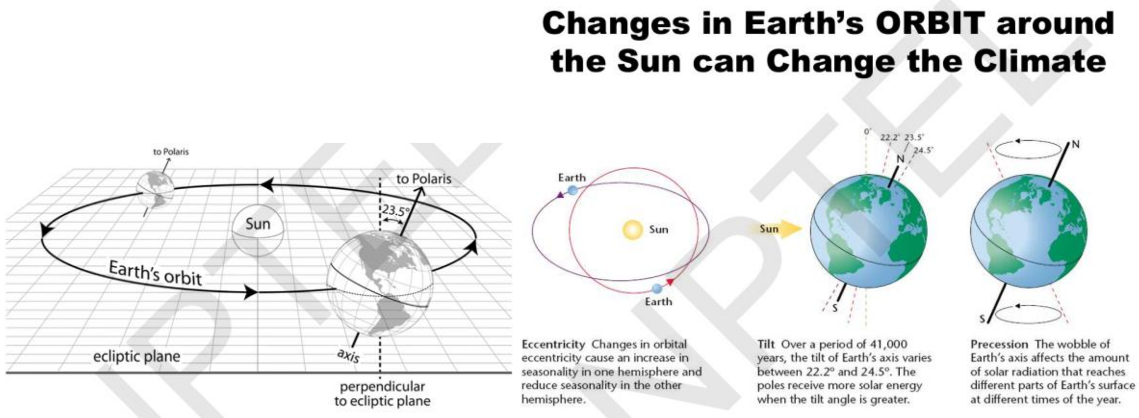
The graph reveals a striking correspondence between periods of low summer insolation and cold glacial periods, and between high insolation and interglacial warm periods. While the correlation is not perfect, four out of six glacial-interglacial cycles in this time frame show a strong alignment, with only two cycles displaying minor offsets. This correlation strongly supports Milankovitch's theory: when summer radiation at high latitudes is low, snow persists and builds up, triggering or maintaining ice ages. Conversely, when insolation increases, as it did after the Last Glacial Maximum (~20,000 years ago), the increased summer warmth initiates melting, leading to deglaciation.

However, there are caveats to interpreting this relationship, particularly concerning the accuracy of the proxy data. While astronomers can calculate Earth's past orbital parameters and solar insolation with high precision, the oxygen-18 record from ocean cores is subject to uncertainties in dating. The assumption that sediment layers are deposited sequentially is generally valid, but the rate of deposition varies over time due to changing ocean conditions, leading to potential errors in the time axis, especially further back in time (e.g., at 600,000 years). These dating uncertainties limit the precision with which we can compare proxy data to orbital forcing, and suggest the need to also examine better-dated intervals for further confirmation.





The geometry of Earth's orbit around the Sun is crucial for understanding how Milankovitch cycles influence ice ages. The Earth's axis of rotation is tilted relative to the plane of its orbit around the Sun (the ecliptic), a feature known as obliquity. In addition to this tilt, the Earth undergoes axial precession, meaning the direction in which the axis points gradually shifts over time, even though the tilt angle itself may remain constant. This precession affects how solar radiation is distributed seasonally, especially in the polar regions, and is an important factor in modulating the amount of summer insolation (incoming solar radiation) received at high latitudes.



Three primary orbital parameters—eccentricity, obliquity, and precession—collectively determine the Earth's climate cycles. A diagram illustrating these elements often exaggerates eccentricity for clarity, though in reality, Earth's orbit is only slightly elliptical (maximum eccentricity ≈ 0.04). Precession operates on a ~23,000-year cycle, causing the orientation of Earth's axis to gradually shift; for example, 10,000 years ago, the Earth's axis pointed toward the star Vega instead of the current Polaris. The tilt (obliquity) of the Earth's axis oscillates between 21.5° and 24.5° over a 41,000-year cycle.

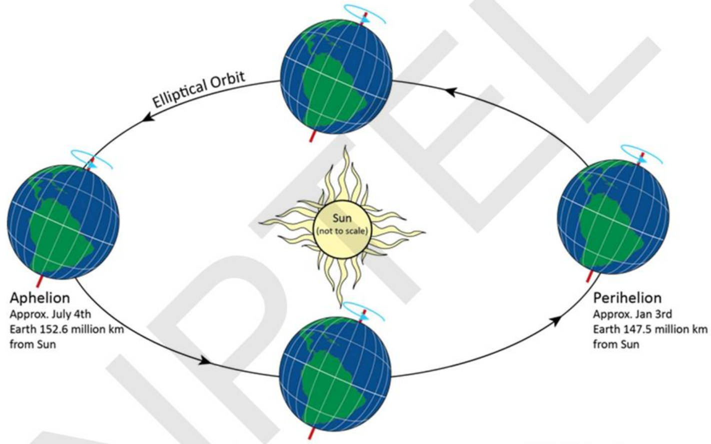
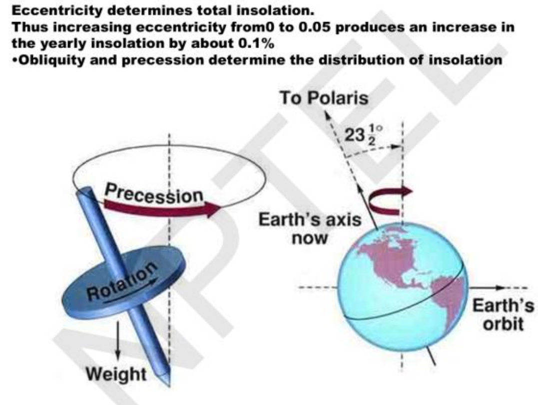


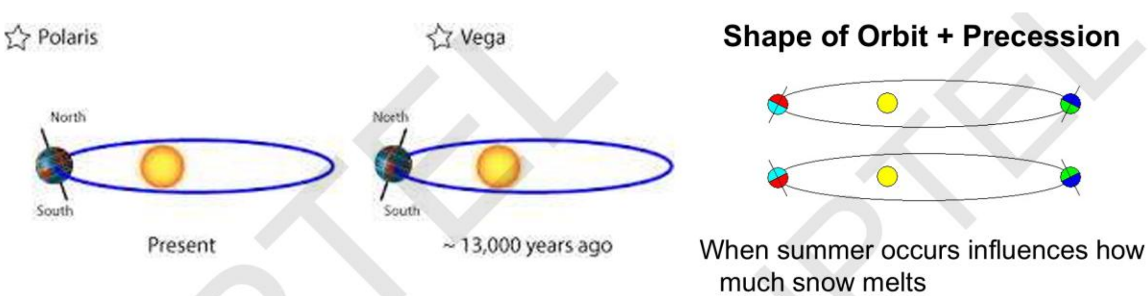
Figure 3.2: Earth's Revolution. Figure by Scott Crosier is licensed under CC BY-NC-SA 4.0

Astronomers also recognize a longer 400,000-year eccentricity cycle, but due to the limited resolution of paleoclimate records, this longer cycle is typically not used in ice age analyses. The key insight is that ice ages are influenced by how much solar radiation reaches the Northern Hemisphere during its summer—a function of Earth's distance from the Sun and its axial orientation. This is demonstrated by the current configuration, where Earth is closest to the Sun (perihelion) around January 3rd (Northern Hemisphere winter), and farthest (aphelion) around July 4th (summer). Despite this, seasonality is primarily governed by axial tilt, not orbital distance. However, ice age cycles are sensitive to the amount of solar radiation during summer in high latitudes, which depends on both eccentricity and precession.



A common source of confusion in understanding Earth's orbital mechanics arises from the distinction between precession and tilt (obliquity). These two are distinct components of the Milankovitch cycles. The tilt refers to the angle between Earth's rotational axis and the perpendicular to its orbital plane, and it varies between 21.5° and 24.5° over a period of 41,000 years. In contrast, precession describes the gradual shift in the direction that the tilted axis points, while the tilt angle itself remains unchanged.

A helpful analogy is the motion of a spinning top. As it spins, the top's axis maintains a steady angle (like Earth's tilt) but slowly sweeps out a circle, changing direction (analogous to precession). For Earth, precession determines when during the orbit the Northern Hemisphere is tilted toward or away from the Sun, affecting seasonal timing. This precession operates on a ~23,000-year cycle and, in combination with eccentricity, influences how much summer radiation reaches the Northern Hemisphere, a key driver in the onset or termination of ice ages.

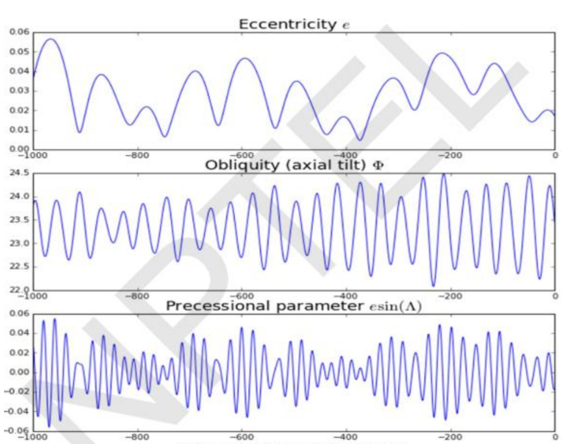


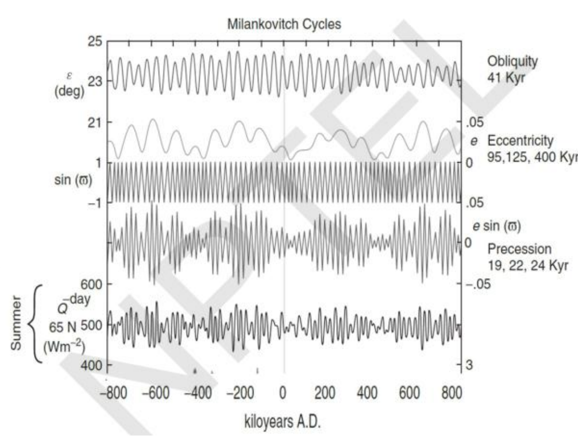
Around 13,000 years ago, a specific orbital configuration occurred that contributed to the end of the last ice age. At that time, the Earth was near perihelion - closest to the Sun, during the Northern Hemisphere's summer. Simultaneously, the Earth's axial precession was such that the axis was pointing toward the Sun, and the North Pole was oriented toward the star Vega rather than the current Pole Star (Polaris). This alignment significantly increased summer insolation at high northern latitudes, enhancing melting of the ice sheets and contributing to the termination of glacial conditions.

By contrast, at present, although summer occurs in July, the Earth is farthest from the Sun (aphelion) during this period, and the North Pole is not tilted toward the Sun, leading to reduced summer radiation at high latitudes. This has led some scientists in the early 20th century to speculate that Earth might soon enter another ice age. However, such a transition is not imminent; based on orbital trends, it would likely take another 10,000 to 20,000 years for such a natural glacial phase to begin. Additionally, anthropogenic global warming could further delay or alter this natural climatic progression.

The periodic changes in the Earth's orbital parameters, obliquity (tilt), precession, and eccentricity, are caused by gravitational influences from celestial bodies in the solar system. The variation in Earth's tilt occurs due to the torque exerted by massive planets, primarily Jupiter and Saturn. Precession, the slow change in the direction of Earth's axial tilt, results from the torques applied by the Moon and the Sun on Earth's equatorial bulge, as the Earth is not a perfect sphere but bulged at the equator. Finally, eccentricity changes (alterations in the shape of Earth's orbit) are mainly due to the gravitational pull of Jupiter and Venus.

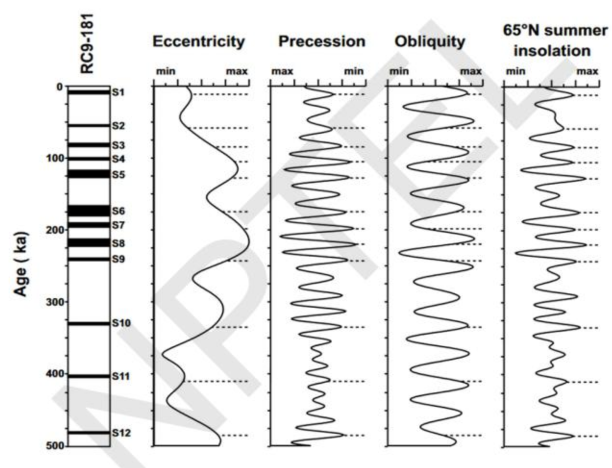
Astronomers have calculated these interactions with high precision. In orbital mechanics, precession is quantified using the "longitude of perihelion", which is the angle between the Earth-Sun line at the vernal equinox and the line connecting the Sun to the perihelion (the point where Earth is closest to the Sun). The additional summer radiation received in the Northern Hemisphere depends on the product of eccentricity and the sine of this longitude. While eccentricity alone does not cause large variations in global radiation, it modulates the effect of precession, making their combined influence significant for determining how much solar radiation reaches the northern polar regions during summer. This explains why Milankovitch correctly emphasized the role of precession, supported by eccentricity, in driving ice age cycles.

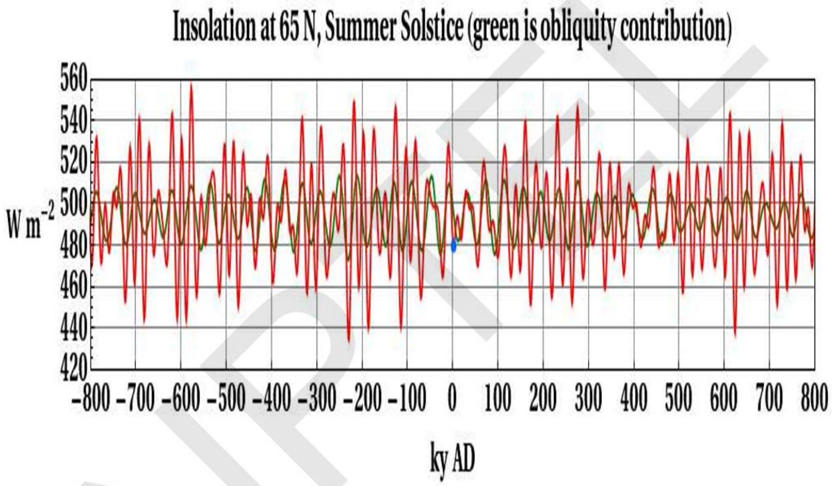




When calculating the changes in Earth's eccentricity, obliquity, and precession, the resulting periodicities are approximately 100,000, 41,000, and 20,000 years, respectively. However, these variations are not perfect sine waves, which indicates the presence of additional, smaller periodic components. For instance, there is a known 400,000-year cycle in eccentricity, and other minor cycles exist as well, though they are often omitted for simplicity. Despite the complexity, the focus is generally maintained on the three dominant cycles that influence long-term climate variability.

When these three factors are combined to calculate the insolation at 65° North latitude, which serves as a proxy for the polar region, the result shows strong modulation by both precession (through the term $Esin(\omega)$, where E is eccentricity and ω is the longitude of perihelion) and obliquity. These control the intensity and duration of summer radiation in the northern polar regions. The computed values of summer insolation vary significantly ranging from 450 to 550 W/m², with an average change of about 40 to 45 W/m². Remarkably, these calculations were originally carried out by hand by Milankovitch, without the aid of calculators or computers, demonstrating both the depth and precision of his work using only astronomical data available in his time.

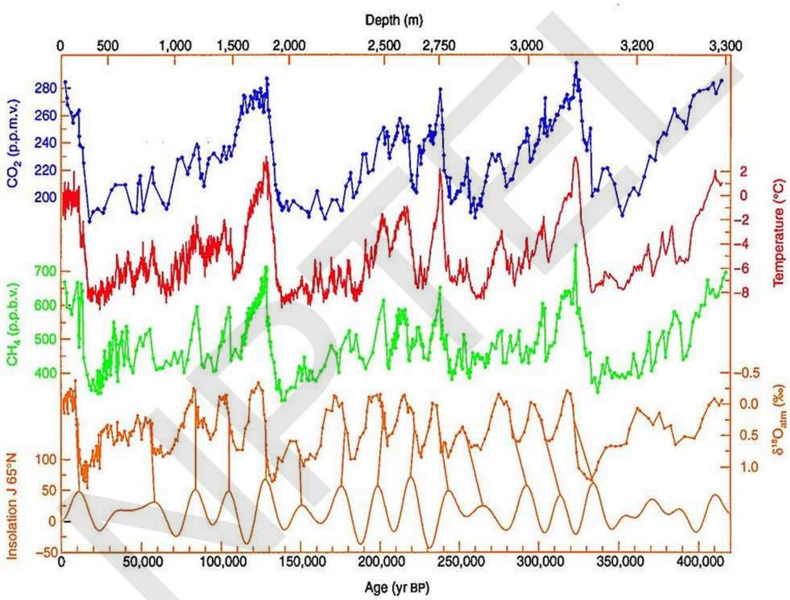




Past and future estimations of daily average insolation at top of the atmosphere on the day of the summer solstice, at 65° N latitude. The green curve is with eccentricity e hypothetically set to 0. The red curve uses the actual (predicted) value of e; the blue dot indicates current conditions (2000 CE).

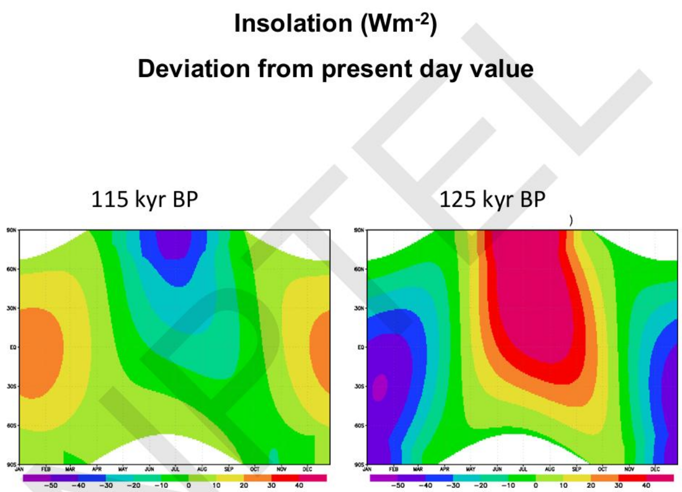
The above figure shows the superposition of insolation at the top of the atmosphere, particularly focusing on how eccentricity and precession modulate the radiation in conjunction with obliquity. A green curve is used to illustrate the hypothetical scenario where eccentricity is set to zero. Under such a condition, precession has no effect, since the term $Esin(\omega)$ becomes zero. This demonstrates that precession only operates when eccentricity is nonzero. If the Earth's orbit were perfectly circular (eccentricity = 0), then even changes in the Earth's axial orientation due to precession would not affect seasonal radiation. Therefore, eccentricity plays a critical enabling role for precession to impact insolation.

The green curve, which represents insolation influenced solely by obliquity (tilt), closely follows the red curve representing the full insolation variation, though with smaller amplitude. This shows that tilt is the primary driver of changes in polar insolation. However, when eccentricity and precession are included, they amplify the effect. For instance, in one scenario, the radiation would be 510 W/m² if only tilt was active, but rises to 540 W/m² due to the combined effect of precession and eccentricity. Thus, while obliquity sets the fundamental pattern of radiation variability, eccentricity and precession introduce additional modulation and increase the amplitude of the variations.



The Vostok ice core data spanning the last 400,000 years provides crucial insights into past climate variations. In the above figure, temperature is shown in red, carbon dioxide (CO_2) in blue, methane (CH_4) in green, oxygen-18 isotope ($\delta^{18}O$) as a proxy for temperature and ice volume, and incoming solar radiation at 65°N curves. While there is some visible correspondence between insolation maxima and changes in $\delta^{18}O$, the most striking feature of this record is the close coupling between temperature, CO_2, and CH_4. All three variables appear to vary in near-synchrony, indicating a strong association between greenhouse gases and global temperature.

However, this dataset does not provide enough temporal resolution to determine the causal direction, that is, whether temperature increases led to rises in CO_2 and CH_4, or whether greenhouse gas concentrations rose first, driving temperature increases via the greenhouse effect. The lack of fine resolution in this long ice core record prevents distinguishing which occurred first. This issue will be addressed in the next lecture using higher-resolution data from the last 20,000 years, which allow clearer identification of the sequence of climate events.



During the last interglacial period, around 125,000 years ago, the northern hemisphere received significantly more solar radiation during summer, about 40 W/m² above the long-term average, particularly toward 90°N. In contrast, the southern hemisphere received less radiation during this period. According to Milankovitch's hypothesis, increased summer insolation in the northern high latitudes leads to the melting of glaciers, thereby ending ice ages. Though one might expect symmetrical effects in both hemispheres, Milankovitch argued that the Northern Hemisphere is more climatically sensitive due to its extensive landmass, which supports the development and instability of large ice sheets. In contrast, the Southern Hemisphere is dominated by oceans, apart from Antarctica, and oceans respond more slowly to changes in radiation due to thermal inertia and deep water mixing.

Around 115,000 years ago, summer insolation in the Northern Hemisphere dropped by about 50 W/m², marking the peak of the subsequent ice age. Over the next 10,000 years, as summer radiation began increasing again, the glacial maximum gradually weakened. This example reinforces Milankovitch’s key insight: it is the summer radiation at high northern latitudes that primarily controls the glacial-interglacial cycles. The continental nature of the Northern Hemisphere allows for more rapid climatic responses to solar forcing compared to the ocean-dominated south.

Despite significant advances in understanding glacial-interglacial cycles, the transition in periodicity of ice ages, from 41,000 years to 100,000 years, remains an unresolved scientific problem. NASA acknowledges that multiple theories have been proposed to explain the shift from ice ages to interglacials, yet no single explanation fully accounts for this transition. The mystery lies in why, despite strong forcing from obliquity (41,000 years), the dominant cycle shifted to eccentricity-linked 100,000-year periods, even though eccentricity itself has a relatively weak direct effect on insolation.

To summarize the mechanisms: the annual mean insolation varies only slightly, proportional to $\frac{1}{\sqrt{1-E^2}}$, and thus cannot alone explain the onset or termination of ice ages. Instead, obliquity (tilt) plays a critical role by causing up to 10% variation in summer insolation at high latitudes. Additionally, the precession parameter, modulated by eccentricity, leads to the $Esin(\omega)$ term, which contributes up to 15% variation in seasonal insolation. Therefore, the combined effect of tilt, eccentricity, and precession can result in up to a 30% variation in summer radiation over the North Pole, a key factor in controlling ice sheet dynamics and glacial cycles.

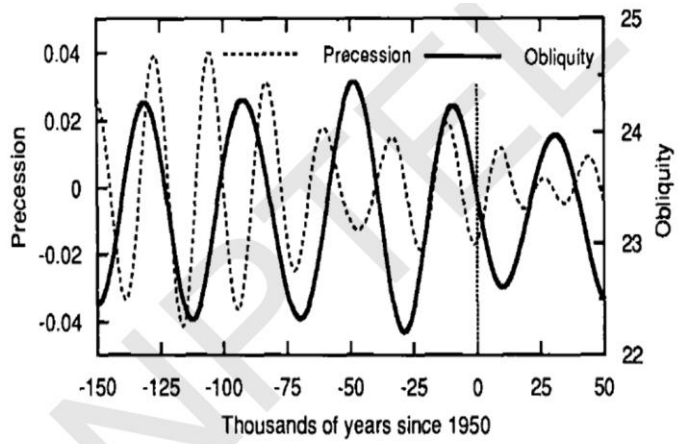
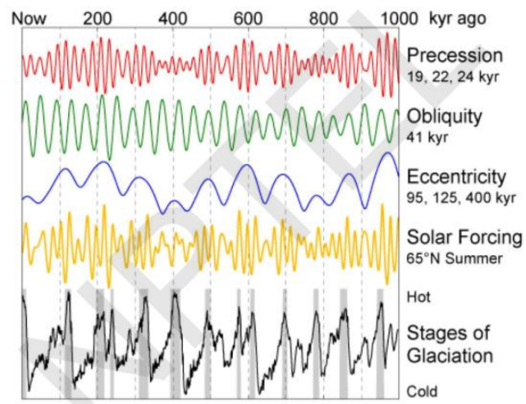


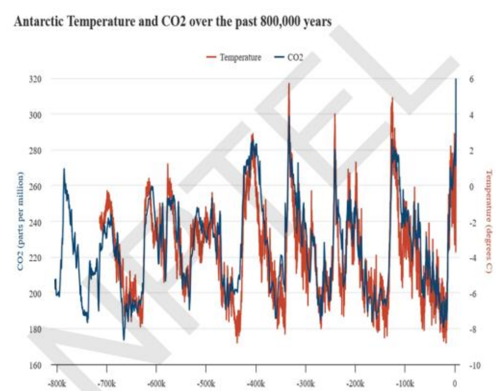
Fig. 11.12 Obliquity (Φ) and precession (e sin Λ) parameters, as functions of time from 150,000 years before present to 50,000 years into the future. Units of obliquity are in degrees.

A key observation when examining the roles of obliquity (axial tilt) and precession in modulating Earth's climate is that these two parameters are not in phase with each other. When the precession effect which modulates the timing and intensity of seasonal insolation, is at its maximum, the obliquity tends to be decreasing. Conversely, when obliquity reaches its maximum value (approximately 24.5 degrees), the influence of precession is on the decline. This asynchrony between the two orbital parameters highlights that their effects on Earth's climate do not reinforce each other consistently over time, but instead alternate in their contributions to variations in insolation, especially at high latitudes. This lack of synchronization has implications for understanding the timing and pacing of glacial and interglacial cycles.

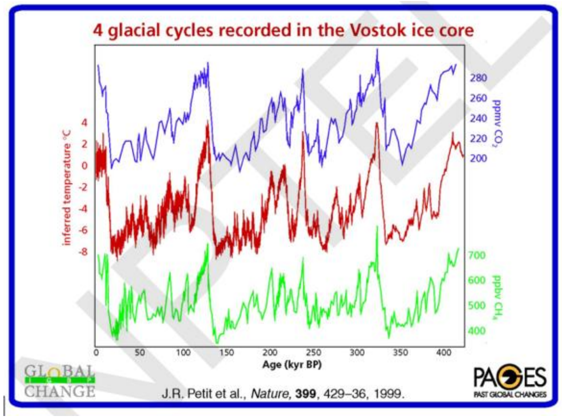


This colorful graph presents the combined influence of precession, obliquity, and eccentricity on the solar radiation received at 65° North latitude, a critical region for ice sheet dynamics. The calculated insolation values show a clear, though not perfect, correspondence with the timing of ice ages. Periods of low radiation align with cold glacial conditions, while sharp transitions to higher radiation coincide with the onset of warmer interglacial periods. This visual correlation underscores that the occurrence and timing of ice ages are governed by the combined effects of all three Milankovitch parameters, tilt, precession, and eccentricity, rather than any one acting alone. Their interplay determines the magnitude and timing of insolation changes, ultimately influencing the growth and decay of ice sheets.

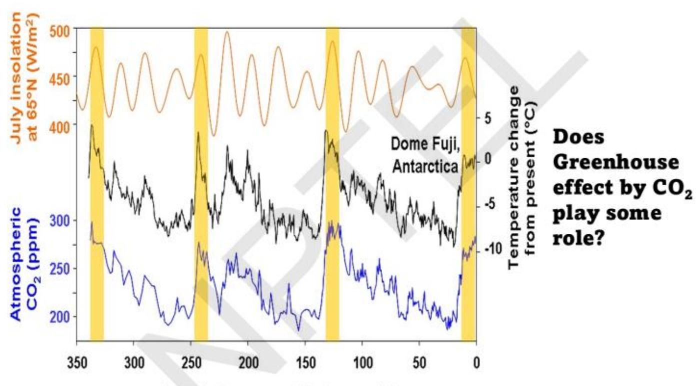
The $\delta^{18}O$ (delta-O-18) isotope ratio is widely recognized as a proxy for global ice volume. Variations in this ratio, measured from ocean sediment or ice cores, reflect changes in the amount of oxygen-18 relative to oxygen-16 in water molecules. During glacial periods, more oxygen-16 is trapped in ice sheets, causing ocean water, and hence marine sediments, to become relatively enriched in oxygen-18. As such, higher $\delta^{18}O$ values typically indicate larger ice volumes, while lower values suggest reduced ice coverage. This makes $\delta^{18}O$ a reliable and widely used indicator of past glacial-interglacial cycles.



When the temperature record from the Antarctic ice core is superimposed with the carbon dioxide (CO_2) concentrations from the same core, a close correspondence is observed between the two variables. This strong correlation suggests that carbon dioxide plays a significant role in regulating temperature over glacial-interglacial cycles. The parallel variations imply that CO_2 is either responding to temperature changes or contributing to them, reinforcing the understanding that greenhouse gases and climate are closely linked. However, the causal direction, whether CO_2 drives temperature or vice versa, remains a critical topic for further investigation.



A graph from the Vostok ice core data displays methane concentrations (in parts per billion) at the bottom and carbon dioxide concentrations (in parts per million) at the top. This visualization once again highlights the close correspondence between greenhouse gas levels, specifically methane and carbon dioxide, and the glacial-interglacial cycles evident in the temperature record. The synchronous variations suggest that these greenhouse gases are closely associated with global temperature changes, reinforcing the hypothesis of their active role in past climate fluctuations.



Additional data from the Dome Fuji ice core further reinforces the understanding of ice age dynamics. This dataset compares the incoming solar radiation at 65°N latitude with atmospheric CO_2 concentrations, revealing a strong correspondence between periods of increased insolation and elevated CO_2 levels. This supports the earlier observations from other ice core records, such as Vostok, highlighting the close relationship between insolation patterns and atmospheric greenhouse gas concentrations during glacial-interglacial cycles.