Climate Change Science
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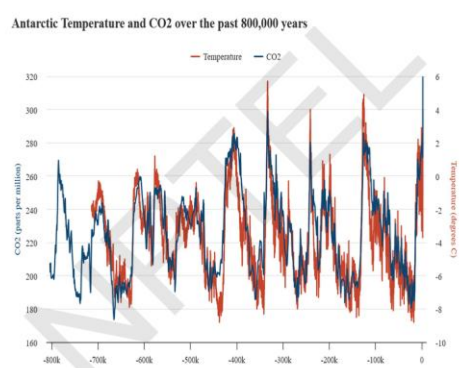
Lecture 33
Milankovitch Theory (continued)

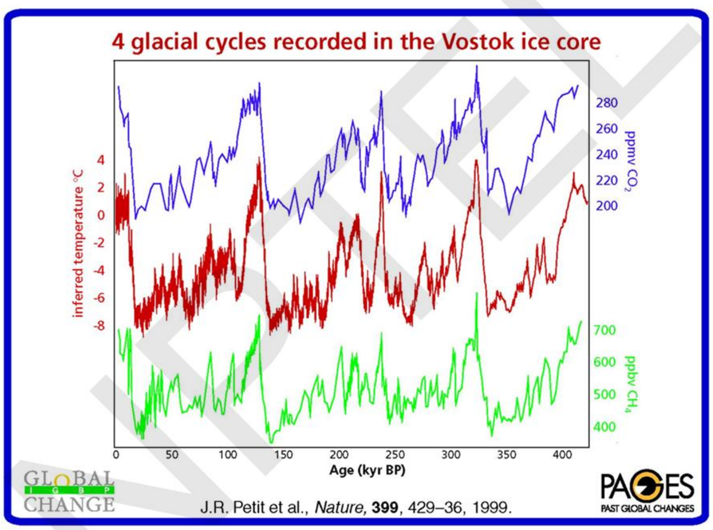
In the previous lecture, the Milankovitch theory was introduced as an explanation for the occurrence of ice ages on Earth. Milutin Milankovitch proposed over a century ago that variations in the Earth's orbit influence the distribution of solar radiation, particularly in the northern polar region, thus driving glacial and interglacial cycles. He identified three key orbital parameters: (1) eccentricity, which affects the Earth-Sun distance and thereby the total solar energy received; (2) obliquity or axial tilt, which determines the intensity of seasonal radiation at higher latitudes, with greater tilt increasing summer insolation in polar regions; and (3) precession, which alters the orientation of the Earth's rotational axis and affects whether the pole is tilted toward or away from the Sun during summer. Although this theory could not be verified at the time due to lack of data, modern ice core records from Antarctica and the Arctic now provide strong evidence in support of it.

These ice cores contain information about past ice volumes inferred from the oxygen-18 isotope ratio ($\delta^{18}O$) in snow deposited in polar regions. As ocean water evaporates and falls as snow, it becomes isotopically lighter i.e., contains less O-18 when more snow accumulates in glaciers. Therefore, $\delta^{18}O$ becomes more negative during periods of greater global ice volume. This relationship is robust and well-established. Independent reconstructions of past sea levels, derived from geological evidence across various coastal sites, show a strong correlation with $\delta^{18}O$ records, confirming that $\delta^{18}O$ is a reliable proxy for global ice volume.

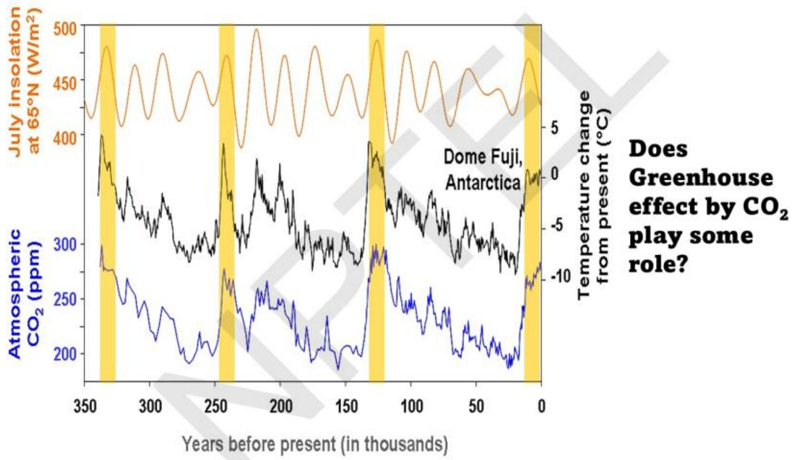


The global ice volume inferred from $\delta^{18}O$ records can also be converted into estimates of global mean temperature. When these temperature estimates are compared with the concentration of CO_2 from air bubbles trapped in ice cores, a close correlation is observed over the past 800,000 to one million years. This marked the first clear evidence that, in addition to orbital changes proposed by Milankovitch, greenhouse gases like CO_2 also play a significant role in the glacial-interglacial cycles. According to ice core records, atmospheric CO_2 concentrations have regularly varied between about 180 ppm and 300 ppm. However, Milankovitch was unaware of these greenhouse gas variations and thus did not include them in his original hypothesis.

In modern understanding, the Milankovitch mechanism is seen as the initial trigger for ice age cycles, with changes in solar insolation at high northern latitudes initiating warming or cooling. Following this trigger, CO_2 and methane, both potent greenhouse gases, act as positive feedbacks. As temperatures rise due to increased summer insolation, CO_2 and methane concentrations also increase, amplifying the warming through enhanced greenhouse effects. Although water vapor is not directly measurable in ice cores, it is understood from the Clausius-Clapeyron relationship that warmer temperatures lead to greater evaporation, increasing atmospheric water vapor, which further enhances the greenhouse effect. Thus, orbital changes serve as the primary driver, and greenhouse gases serve as amplifying feedbacks in the Earth's climate system.



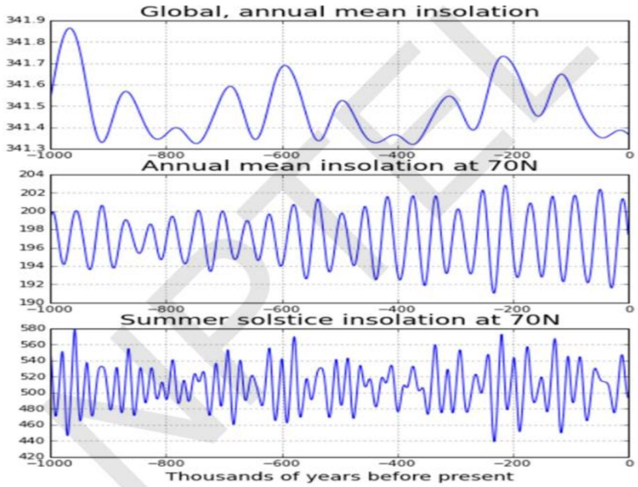
A recapitulation of the Vostok ice core data discussed previously, highlights the variations in temperature (red curve), carbon dioxide (blue), and methane (green) over glacial-interglacial timescales. All three parameters exhibit a close coupling, with their patterns rising and falling in synchrony. This strong correlation underscores the close relationship between temperature and greenhouse gas concentrations. However, the temporal resolution of the Vostok data is insufficient to determine causality, that is, whether increases in carbon dioxide and methane followed or preceded changes in temperature. Due to this limitation, it is not possible to conclude from this dataset whether the greenhouse gas concentrations caused the temperature changes or were themselves a response to the temperature variations. This critical question will be addressed in the next lecture, using higher-resolution data from the last 20,000 years, which allows more precise determination of the timing and sequence of events.



We revisit the ice core data for carbon dioxide (in blue) and temperature from Dome Fuji, Antarctica (in black), along with the incoming solar radiation at 65°N in July over the past 350,000 years. Although the temperature data comes from Antarctica, the radiation data from the Northern Hemisphere is used because, according to Milankovitch's hypothesis, the trigger for ice ages originates in the Northern Hemisphere. This is due to the land-dominated geography of the Northern Hemisphere, which has low heat capacity, making it more sensitive and responsive to changes in insolation. In contrast, the Southern Hemisphere is ocean-dominated, which means it has higher heat capacity and slower response to radiation changes.

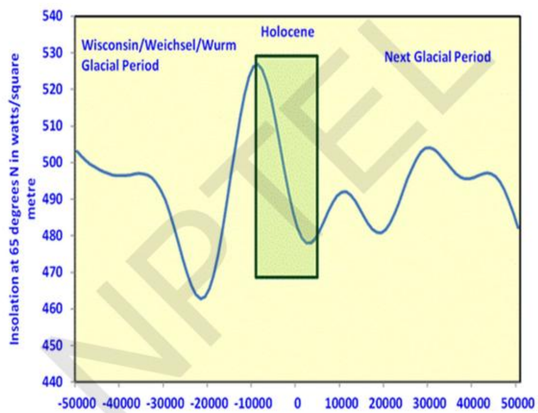
The graph shows a notable correspondence between peaks in northern hemisphere summer insolation and temperature trends in Antarctica. During periods of high insolation at 65°N, Antarctic temperatures tend to peak and begin to decrease as insolation decreases. However, this correlation is not perfect. There are exceptions, such as radiation peaks that do not lead to temperature increases, or blips in temperature that do not correspond to changes in radiation. This implies that other processes also influence climate variability.

One such process is the Atlantic Meridional Overturning Circulation (AMOC), which transports heat from the Southern Hemisphere to the Northern Hemisphere. This interhemispheric heat transport can alter the timing and magnitude of temperature changes, especially in Antarctica. The comparison thus supports the view that Northern Hemisphere summer insolation serves as the primary trigger, while additional factors like ocean circulation modulate the global temperature response.



The incoming global mean solar radiation over the last one million years has shown only minor variations, primarily due to averaging over all latitudes and longitudes. The mean value is around 341.5 W/m², with fluctuations limited to a narrow range between 341.3 and 341.9 W/m², amounting to a difference of just 0.6 W/m². This minimal variation indicates that global mean insolation is insufficient to explain the occurrence of ice ages. Recognizing this, Milankovitch focused not on the global mean but on more regionally and seasonally specific radiation metrics.

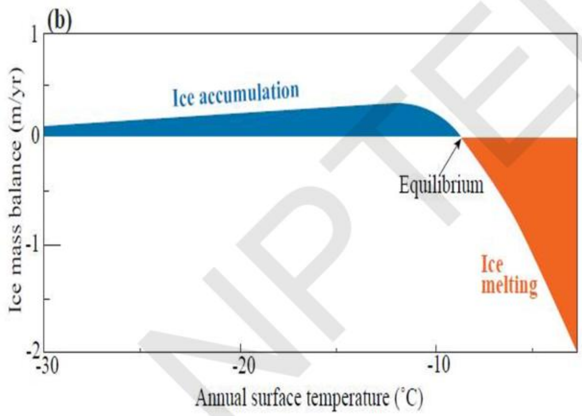
The annual mean radiation at 70°N shows slightly more variation of about 6 W/m² but still not enough to act as a primary driver. The most significant variations are found in summer solstice insolation at 70°N, specifically in June. This summer radiation varies dramatically between 440 and 580 W/m², a change of approximately 140 W/m², or about 30 percent. Such a large variation is critical because it directly influences the melting or growth of ice sheets in the high northern latitudes. Consequently, Milankovitch focused his hypothesis on summer insolation at 65–70°N, rather than on the global or annual mean values, as this more accurately represents the seasonal triggers that can initiate or end ice ages.



A close examination of the last 20,000 years, a crucial period marking the end of the last ice age, reveals a significant increase in summer insolation at 65°N. Around 20,000 years ago, the incoming solar radiation in the polar region increased sharply from approximately 460 W/m² to about 525 W/m², a rise of nearly 60–70 W/m². This substantial increase is considered to have triggered the collapse of the last glacial period. Following this peak, the radiation levels have gradually declined over the past 10,000 years, with a decrease of around 60 W/m². However, this decline in insolation has not led to a resurgence of ice in the Northern Hemisphere.

This asymmetry in the climate system's response where an increase in radiation leads to deglaciation, but a subsequent decrease does not reverse the process highlights the non-linear nature of Earth's climate system. The climate does not respond symmetrically to rising and falling radiation levels. This non-linearity is a crucial concept in understanding both the onset and termination of ice ages, emphasizing that the climate system contains feedbacks and thresholds that modulate its response to external forcing.

Asymmetry in accumulation and melting



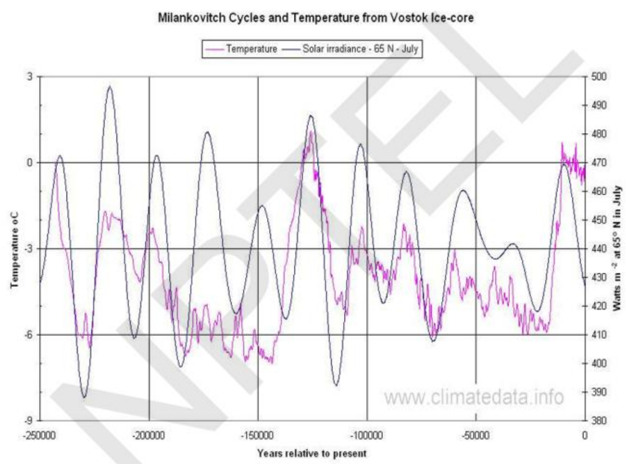
When temperature is very low there will be NO snowfall because the amount of moisture in the air is low. When the temperature is above 0 deg C, ice will start melting. Hence there is a narrow range of temperatures when the ice can accumulate in the polar region

Figure from Ruddiman

To understand the asymmetry in ice accumulation and melting, it is important to consider the relationship between temperature, humidity, and snowfall in the polar regions. At very low temperatures, such as –30°C, the atmosphere holds very little water vapor, as governed by the Clausius-Clapeyron equation. Consequently, snowfall is minimal under such cold conditions due to insufficient humidity. This explains why Antarctica, being extremely cold, currently experiences very little snowfall, especially compared to the Arctic.

As the temperature increases from –30°C to about –20°C, the air's humidity rises, leading to a gradual increase in snowfall. Ice accumulation reaches a peak around –15°C to –5°C, where the conditions are ideal for consistent snowfall that accumulates year after year. However, once the temperature increases beyond this range, particularly past –10°C, melting begins and snowfall starts to decline. This results in a sharp increase in melting rate, much steeper than the gradual accumulation rate.

This disparity in slopes highlights a fundamental non-linearity: ice builds up slowly over thousands of years, but melts rapidly when the temperature crosses a certain threshold. The asymmetric response is due to the narrow temperature window that favours accumulation and the accelerated melting that follows once the threshold is exceeded. Importantly, the temperature values discussed refer to annual mean temperatures; a mean of –10°C, for instance, implies much warmer summer temperatures, which are critical for melting. This conceptual understanding is illustrated in the above figure from Ruddiman’s book, previously referenced in the lecture.



Revisiting the Vostok ice core data, a comparison is made between the incoming solar radiation at 65° North (black line) and the Antarctic temperature inferred from oxygen-18 isotopic abundance (pink curve). In some instances, such as around 130,000 years ago, there is a clear correspondence between the peaks of solar radiation and Antarctic temperature, lending strong support to the Milankovitch hypothesis. According to Milankovitch, maximum radiation during July in the northern polar region (Arctic) leads to maximum temperature in the southern polar region (Antarctica). This relationship underscores the interconnectedness of the two hemispheres, facilitated by both oceanic heat transport and atmospheric circulation. Additionally, greenhouse gases like carbon dioxide and methane, which are well-mixed globally, help reinforce this linkage. An increase in CO_2 concentration in the northern hemisphere would similarly impact the southern hemisphere, contributing to global climate feedbacks.

However, this correspondence is not consistent throughout the ice core record. For example, around 100,000 years ago, the temperature peak is much smaller despite a peak in radiation. At 60,000 years ago, the temperature peak does not align with the solar radiation peak at all. Conversely, over the last 20,000 years, there is once again a strong match between the peak in Antarctic temperature and the peak in solar radiation around 10,000 years ago.

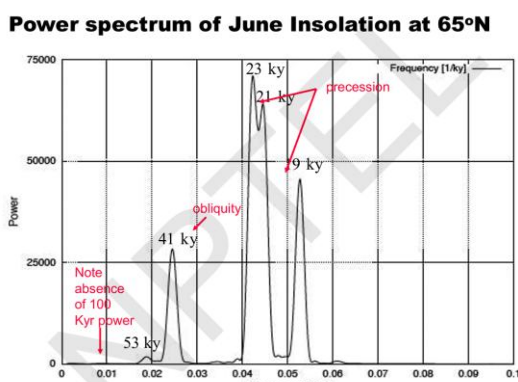
These observations suggest that while Milankovitch was correct in identifying northern hemisphere summer insolation as the primary driver of glacial cycles, the climate system is more complex. The lack of perfect alignment between radiation and temperature peaks implies that additional processes, such as internal climate feedbacks, atmospheric composition, and oceanic dynamics, must also be taken into account for a complete understanding of ice age dynamics.

To further understand the relationship between solar radiation and ice age temperature cycles, it is necessary to examine the spectra, i.e., the periodicity of both temperature and solar radiation variations. This can be explored through a simple energy balance model applied specifically to the polar regions:

$$\frac{dT}{dt} = S(t) \times (1 - albedo) - OLR$$

Here, $S(t)$ represents the time-varying incoming solar radiation at the poles, $(1 - albedo)$ gives the absorbed fraction, and OLR is the outgoing longwave radiation. Because this model is meant for polar regions, there is no division by 4, unlike in global energy balance models.

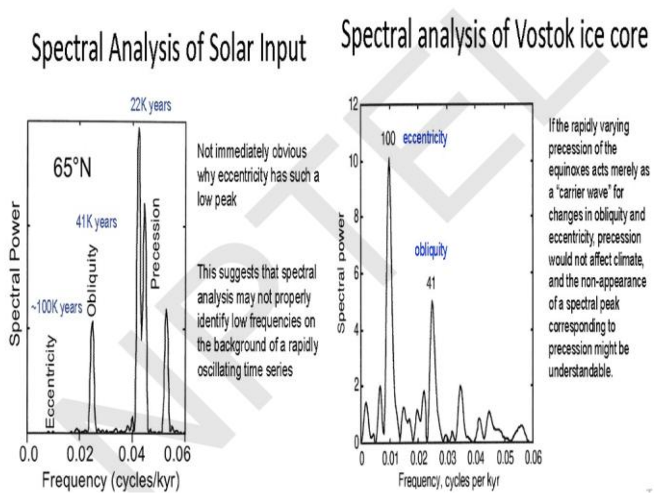
To simplify, variations in $albedo$ and OLR with time are temporarily ignored, allowing focus solely on how temperature responds to changes in incoming radiation. Under these assumptions, one might expect a linear relationship between solar radiation $S(t)$ and temperature T. Therefore, if one performs a Fourier spectral analysis of $S(t)$ by decomposing the solar radiation into its Milankovitch cycles of eccentricity (~100,000 years), obliquity or tilt (~41,000 years), and precession (~23,000 years), then the temperature signal should exhibit similar periodic variations. This forms the basis for testing the Milankovitch theory, by checking whether the climatic temperature record (e.g., from ice cores) shares the same dominant spectral components as the solar forcing, reinforcing the idea that orbital variations drive glacial-interglacial cycles.



An analysis of the power spectrum of June solar radiation at 65°N latitude, derived from Milankovitch's orbital calculations, reveals distinct peaks corresponding to different orbital cycles. The largest spectral peak is seen around 20,000 years, which aligns with the precession cycle. The next most prominent peak appears near 40,000 years, corresponding to the obliquity (tilt) cycle. Interestingly, there is almost no spectral power at 100,000 years, which is the timescale of Earth's eccentricity cycle. According to Milankovitch’s hypothesis, one would thus expect the dominant temperature variations in glacial cycles to occur at 20,000 and 40,000-year intervals.

However, observations from Antarctic and Arctic temperature reconstructions (e.g., from ice core records) over the last million years show that the strongest periodicity in the glacial-interglacial temperature cycle lies at the 100,000-year timescale. This creates a paradox: the orbital forcing (insolation) spectrum shows little to no energy at 100,000 years, yet the climate system’s temperature response is dominated by this very cycle. This discrepancy is a central puzzle in paleoclimatology and suggests that factors beyond direct solar forcing, such as feedbacks and internal Earth system dynamics, must be amplifying the response at this timescale.

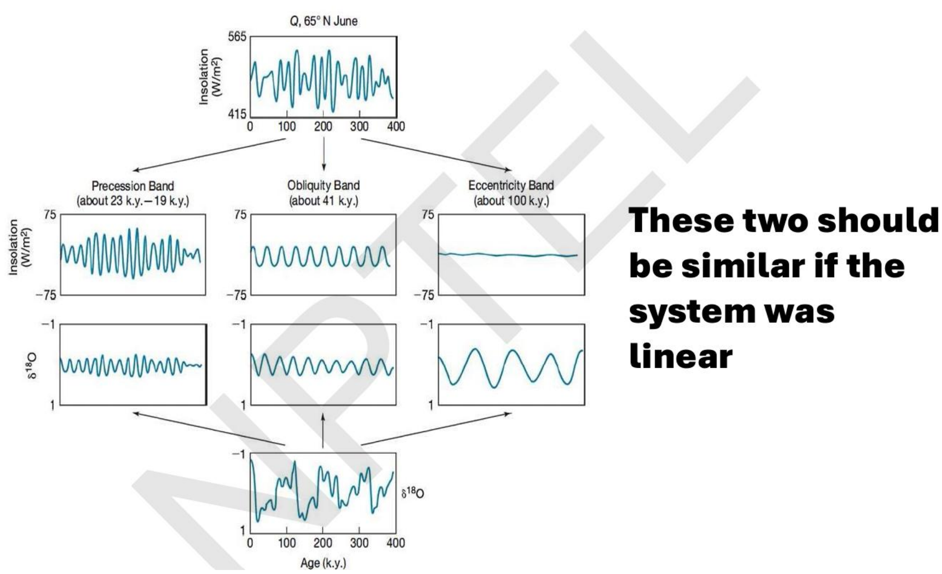
It is also worth noting that while the power spectrum explicitly shows components near 23,000, 21,000, and 19,000 years (all related to precession), the discussion simplifies these into a single representative 20,000-year cycle for ease of understanding. In reality, the Earth's orbital parameters involve multiple subtle periodicities, which contribute to the complexity of the climate response.



A direct comparison between the spectral power of incoming solar radiation at 65°N and that of the temperature proxy ($\delta^{18}O$ data from ice cores) reveals a striking mismatch in periodicities. The solar radiation spectrum, dominated by precession (~20,000 years) and obliquity (~40,000 years) cycles, exhibits little to no power at the eccentricity timescale (~100,000 years). In contrast, the $\delta^{18}O$ record, which reflects global ice volume and temperature, shows its strongest spectral power at 100,000 years, with a secondary peak at 40,000 years and almost no power at 20,000 years. This clear discrepancy poses a challenge to the Milankovitch hypothesis, which suggests that orbital forcing alone should explain glacial cycles.

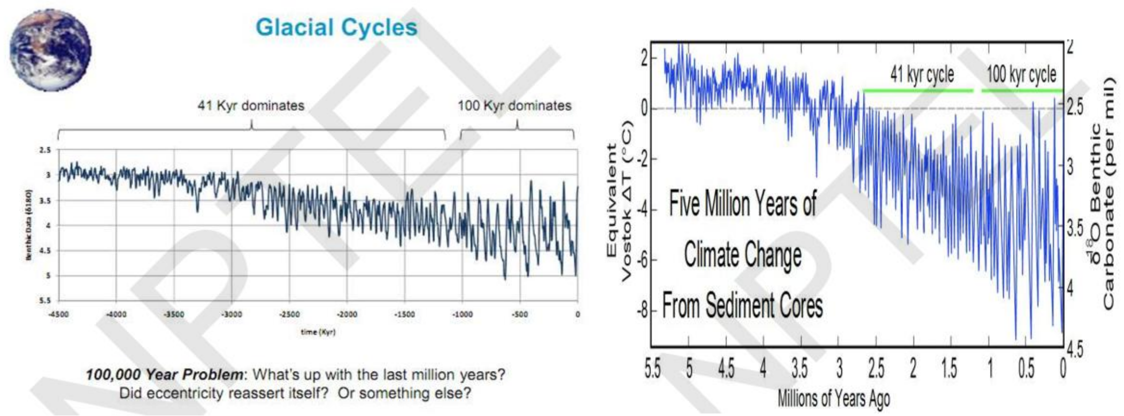
However, it is important to note that over a longer geologic period between 1 million and 5 million years ago the dominant periodicity in the $\delta^{18}O$ spectrum was indeed around 40,000 years, aligning well with the tilt cycle, as Milankovitch originally proposed. This indicates that the Milankovitch hypothesis may have been more valid in earlier epochs, where the Earth's climate system may have been more linearly responsive to orbital forcing. The transition to 100,000-year dominance in the last 1 million years despite the lack of corresponding power in the insolation spectrum suggests a nonlinear response of the climate system, possibly involving internal feedback mechanisms, ice sheet dynamics, or threshold effects.

The challenge, therefore, is to understand why, during the last million years, the climate system began to exhibit such strong 100,000-year cycles, despite this frequency being absent in direct solar forcing.



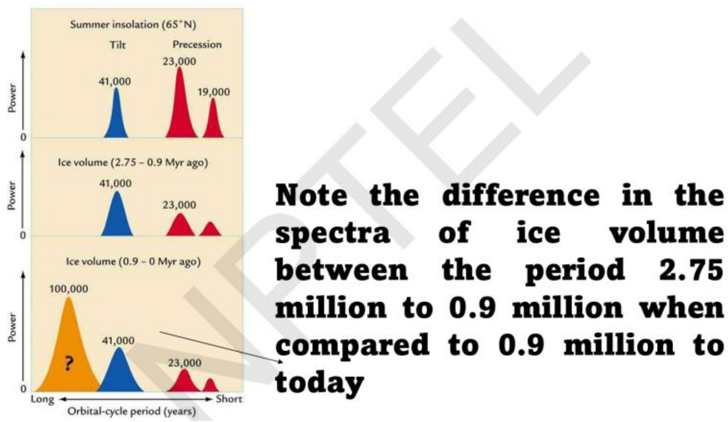
Another comparison between incoming solar radiation at 65°N in June and the $\delta^{18}O$ temperature proxy is depicted above which reinforces the key paradox: the radiation spectrum shows strong power at ~20,000 years (precession), moderate power at ~40,000 years (obliquity), and almost no power at ~100,000 years (eccentricity). However, the $\delta^{18}O$ spectrum, representing global ice volume and temperature, displays the strongest peak at 100,000 years, a moderate peak at 40,000 years, and minimal power at 20,000 years. This mismatch indicates that the Earth’s climate system does not respond linearly to solar insolation variations. If the system were linear, the spectral power in temperature should closely mirror that of the incoming radiation. The fact that they differ so markedly implies the presence of non-linear dynamics within the Earth system.

It is reiterated again that in order to explain the observed 100,000-year periodicity in glacial-interglacial cycles during the last million years, despite the absence of a corresponding signal in the solar forcing, non-linear mechanisms must be considered. These may include threshold behaviours, feedback loops involving ice sheets, CO_2-climate interactions, and internal variability in ocean-atmosphere circulation. Understanding which of these non-linear processes are responsible is essential for explaining the nature of Quaternary ice ages.



A long-term record of $\delta^{18}O$ from deep ocean sediment cores, spanning the last 4.5 million years, reveals a significant shift in the dominant periodicity of Earth's glacial cycles. Prior to 1 million years ago, the $\delta^{18}O$ data show a strong dominance of the 40,000-year cycle, consistent with the obliquity (tilt) component of Milankovitch forcing. However, during the last 1 million years, the dominant periodicity shifts to 100,000 years, which does not align with significant power in the solar insolation spectrum. This transition marks the onset of the "100,000-year problem", where the observed glacial cycles are no longer directly explained by Milankovitch orbital forcing alone.

Despite this mismatch, the Milankovitch hypothesis remains valid as the primary trigger for ice ages, particularly through variations in summer insolation at 65°N. However, it is now evident that additional processes including greenhouse gas feedbacks, ice sheet dynamics, and ocean circulation changes, play crucial roles in shaping the Earth's glacial-interglacial cycles. These processes introduce non-linear responses that modulate the basic orbital forcing, altering the spectral characteristics of the temperature record. This further emphasizes the complexity of Earth's climate system beyond linear Milankovitch forcing.



To reiterate the central paradox, the spectral analysis of summer incoming solar radiation at 65°N reveals a strong peak at ~20,000 years (associated with precession), a moderate peak at ~40,000 years (obliquity), and negligible power at 100,000 years (eccentricity). In contrast, the $\delta^{18}O$ record, which serves as a proxy for global ice volume and temperature over the last million years, displays its dominant spectral power at 100,000 years, with lesser peaks at 41,000 years and minimal response at 20,000 years. This lack of correspondence between the forcing (solar insolation) and the response (ice volume) in the most recent million years highlights a fundamental discrepancy that cannot be explained by Milankovitch's original linear framework.

While some level of correspondence exists in the period between 1 million and 2.7 million years ago, it clearly breaks down in the last million years. Therefore, to resolve this inconsistency, it becomes necessary to invoke non-linear mechanisms within the Earth system that modulate the climate's response to orbital forcing. The upcoming discussion will focus on identifying and analyzing such non-linear feedbacks and processes that might explain this 100,000-year periodicity in glacial cycles.