Glacial Cycles
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Temperatures in the Cenozoic Era


18O as a Climate Proxy

The isotope 18O preferentially evaporates from the ocean and is sequestered in glaciers, leaving the heavier isotope 16O more heavily concentrated in the ocean. Thus oceanic concentration of the isotope 18O is higher during glacial periods.

Foraminifera absorb more 18O into their skeletons when the water temperature is lower and when more 18O is in the water.

Thus higher concentrations of 18O in foraminifera fossils indicate lower ocean temperatures and higher glacier volume.

18O in Foraminifera Fossils During the Past 4.5 Myr


Recent (last 400 Kyr) Temperature Cycles

What Causes Glacial Cycles?

Widely Accepted Hypothesis
The glacial cycles are driven by the variations in the Earth’s orbit (Milankovitch Cycles), causing a variation in incoming solar radiation (insolation).
This hypothesis is widely accepted, but also widely regarded as insufficient to explain the observations.
The additional hypothesis is that there are feedback mechanisms that amplify the Milankovitch cycles. What these feedbacks are and how they work is not fully understood.
**Glacial Cycles**

**Eccentricity**

- Perihelion: 91.5
- Aphelion: 94.5
- Change in radius: \( \frac{3}{93} = 3.2\% \)
- Change in insolation: 6.4%
- Six percent less insolation in the southern winter than the northern winter.

6.4% of 342 Wm\(^2\) = 22 Wm\(^2\)

**Glacial Cycles**

**Global Annual Average Insolation**

**Solar output:**

\[ K \text{ Watts} \]

**Solar intensity at distance } r \text{ from the sun:}

\[ \Phi(r) = \frac{K}{4r^2} \text{ Wm}^{-2} \]

**Cross section of Earth:** \( x_r \text{ m}^2 \)

**Global solar input:** \( \frac{Kx_r}{4} \text{ W} \)

**Total annual solar input (} P \text{ = one year (in seconds)):}

\[ \int_0^\pi \frac{Kx_r}{4} \cos \theta \, d\theta = \frac{Kx_r}{4} \int_0^\pi \cos \theta \, d\theta \text{ Joules} \]

**Mean annual solar intensity on the Earth’s surface:**

\[ \frac{\pi Kx_r}{2P^2} \frac{1}{4\pi} K \text{ Wm}^{-2} \]

**Global Annual Average Insolation**

**Specific angular momentum (angular momentum per unit mass):**

\[ \Omega = r \dot{\theta} \text{ m/s} \]

**Total annual solar input:**

\[ \frac{Kx_r}{2P^2} \int_0^\pi \frac{dt}{r^2} = \frac{Kx_r}{2P^2} \int_0^\pi \frac{dt}{\cos \theta} = \frac{Kx_r}{2P^2} \text{ Joules} \]

**Mean annual solar input:**

\[ \frac{\pi Kx_r}{2P^2} \text{ Watts} \]

**Mean annual solar intensity on the Earth’s surface:**

\[ \frac{\pi Kx_r}{2P^2} \frac{1}{4\pi} K \text{ Wm}^{-2} \]

**Glacial Cycles**

**Global Annual Average Insolation**

**Kepler’s Third Law:**

\[ p^2 \sim a^3 \quad a = \text{semimajor axis} \]

Derived from Kepler:

\[ 1 - e^2 \sim \Delta t^2 \quad e = \text{eccentricity} \]

**Mean annual solar intensity:**

\[ \frac{K}{8P^2} \frac{Kx_r}{2P^2} \frac{1}{\sqrt{1 - e^2}} \frac{\cos \theta}{\sqrt{1 - e^2}} \text{ Wm}^{-2} \]

**Laskar:**

Fig. 11. Variation of the semi-major axis of the Earth–Moon barycenter (in AU) from \(-250 \text{ to } 2,250 \text{ Myr} \).

Semi major axis does not change much:

.005% corresponding to .01% change in global average insolation


**Glacial Cycles**

**Eccentricity**

2.2%
Glacial Cycles

Obliquity

Note period of about 41 Kyr.


Precession Index

index = e \sin \rho, \text{ where } e = \text{ eccentricity and } \rho = \text{ precession angle (measured from spring equinox)}

Note period of about 23 Kyr.


Daily Average Insolation at Summer Solstice at 65° N

http://en.wikipedia.org/wiki/Milankovitch_cycles

Glacial Cycles

Daily Average Insolation at Summer Solstice at 65° N

Insolation at a point on the Earth’s surface

\[ I(\beta, \rho, \phi, \theta, e, q) = \frac{A}{2} \left[ -\cos(\alpha) \cos(\beta - \rho) \cos(\gamma) + \sin(\alpha) \sin(\beta - \rho) \sin(\gamma) \right] \]

\( (\phi, \gamma) = \text{position of Earth in orbital plane} \)

\( \beta = \text{obliquity angle} \)

\( \rho = \text{precession angle} \)

Daily average insolation at latitude \( \phi \) at summer solstice

\[ T(e, \beta, \rho, \phi) = \frac{1}{2} \int _{0}^{2\pi} \left[ \cos q \cos \beta \cos \gamma + \sin \beta \cos \rho \phi \right] dq \]

Glacial Cycles

Daily Average Insolation at Summer Solstice at 65° N

Solar Forcing (Hays, et al)

Three different temperature proxies from sea sediment data.


1) Three indices of global climate have been monitored in the record of the past 450,000 years in Southern Hemisphere ocean-floor sediments.

2) ... climatic variance of these records is concentrated in three discrete spectral peaks at periods of 23,000, 42,000, and approximately 100,000 years. These peaks correspond to the dominant periods of the earth's solar orbit, and contain respectively about 10, 25, and 50 percent of the climatic variance.

3) The 42,000-year climatic component has the same period as variations in the obliquity of the earth's axis and retains a constant phase relationship with it.

4) The 23,000-year portion of the variance displays the same periods (about 23,000 and 19,000 years) as the quasiperiodic precession index.

5) The dominant, 100,000-year climatic component has an average period close to, and is in phase with, orbital eccentricity. Unlike the correlations between climate and the higher-frequency orbital variations (which can be explained on the assumption that the climate system responds linearly to orbital forcing), an explanation of the correlation between climate and eccentricity probably requires an assumption of nonlinearity.

6) It is concluded that changes in the earth's orbital geometry are the fundamental cause of the succession of Quaternary ice ages.

7) A model of future climate based on the observed orbital-climate relationships, but ignoring anthropogenic effects, predicts that the long-term trend over the next seven thousand years is toward extensive Northern Hemisphere glaciation*

*Quoted by George Will, Washington Post, February 5, 2009


A. Power spectrum of climate for the last 4.5 Myr. Note the peaks at 41Kyr and 100 Kyr.

B. Power spectrum of climate for the period 25 Myr bp to 20.5 Myr bp. Note the new peak at 400 Kyr and the “split” peaks at 126Kyr and 95 Kyr.

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Summary

The solar forcing, defined as the maximum insolation at latitude 65° N, is dominated by precession, followed by obliquity, followed by eccentricity.

The climate response is dominated by eccentricity, followed by obliquity, followed by precession (Hays) OR obliquity, followed by eccentricity, with negligible precession (Zachos).

The explanation is that there are nonlinear feedbacks. The total annual solar input depends mainly on eccentricity, and a little bit on semimajor axis, but not at all on obliquity or precession.

Is maximum insolation at latitude 65° N the appropriate forcing? What nonlinear feedbacks?

to be continued ...