Glacial Cycles

Temperatures in the Cenozoic Era

Foraminifera absorb more $^{18}$O into their skeletons when the water temperature is lower and when more $^{18}$O is in the water. Thus higher concentrations of $^{18}$O in foraminifera fossils indicate lower ocean temperatures and higher glacier volume.

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

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Glacial Cycles

$^{18}$O in Foraminifera Fossils During the Past 4.5 Myr

$^{18}$O in Foraminifera Fossils During the Past 1.0 Myr

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**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 and/or triggering mechanisms that amplify the Milankovitch cycles. What these feedbacks are and how they work are not fully understood.

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**Heat Balance**

Historical Overview of Climate Change Science, IPCC AR4, p.96


**Eccentricity**


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**Eccentricity**

Perihelion: 91.5x10^6 mi
Aphelion: 94.5x10^6 mi
Semimajor axis: 93x10^6 mi
Eccentricity: 1.5/93 = 0.016

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**Eccentricity**

Penhelion: 91.5
Aphelion: 94.5
Change in radius: 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 W/m² = 22 W/m²
Earth’s Orbit

Kepler’s First Law: The orbit of every planet is an ellipse with the Sun at one of the two foci.

Eccentricity = c/a

Johannes Kepler (1571-1630)

Eccentricity = c/a

Specific angular momentum (angular momentum per unit mass):

\[ \Omega = r^3 \dot{\theta} \text{ m}^2 \text{s}^{-1} \]

Total annual solar input:

\[ \int_{0}^{2\pi} K r^2 \frac{dt}{r(t)} \]

Mean annual solar input:

\[ \frac{\pi K r^2}{2 \nu^2} \text{ Watts} \]

Mean annual solar intensity on the Earth’s surface:

\[ \frac{\pi K r^2}{2 \nu^2} \frac{1}{r^2} \text{ W m}^{-2} \]

Kepler’s Third Law:

\[ p^3 = a^2 \]

\[ \text{Derived from Kepler:} \]

\[ 1 - e^2 = \frac{4 \pi^2 K r^2}{a^3} \]

Mean annual solar intensity:

\[ \frac{K}{8 \nu^2} \frac{1}{\sqrt{1 - e^2}} \text{ W m}^{-2} \]

Semi major axis does not change much:

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


The orbits of all the planets can be computed (both forward and backward in time) for billions of years.
The effect due to eccentricity is more significant, but not that much: As \( e \) varies between 0 and 0.06, \((1-e^2)^{-1/2}\) varies between 1 and 1.0018, or about 0.2%. (Twenty times the effect due to \( a \).)


The period of about 100 kyr and 400 kyr.

The obliquity cycle shows a period of about 100 kyr and 400 kyr. The effect due to obliquity is more significant, but not that much: As \( \alpha \) varies between 0 and 0.06, \((1-\sin^2 \alpha)^{-1/2}\) varies between 1 and 1.0018, or about 0.2%. (Twenty times the effect due to \( e \).)


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Eccentricity


Glacial Cycles

Daily Average Insolation at Summer Solstice at 65° N

Insolation at a point on the Earth’s surface

\[ I(\beta, \rho, \varphi, \theta, r, \phi) = \frac{k}{4\pi r^2} \left[ \cos \varphi \left( \cos \beta \cos (\theta - \rho) \cos \gamma - \sin (\theta - \rho) \sin \gamma \right) - \sin \varphi \sin \beta \cos (\theta - \rho) \right] \]

\((\varphi, \rho) = \text{latitude, longitude}\)

\((\rho, \theta) = \text{position of Earth in orbital plane}\)

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

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

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

\[ T(\epsilon, \beta, \rho', \varphi) = \frac{1}{2} \left[ \frac{1 - \epsilon}{1 + \epsilon} \right] \int_{\rho'}^{\rho} \left[ 1 + \epsilon \cos \beta \cos \gamma + \sin \varphi \sin \beta \right] d\rho \]

Glacial Cycles

Who was Milankovitch?

Milutin Milankovitch was a Serbian mathematician and professor at the University of Belgrade.

In 1920 he published his seminal work on the relation between insolation and the Earth's orbital parameters.

In 1941 he published a book explaining his entire theory.

His work was not fully accepted until 1976.

What happened in 1976?


“It is concluded that changes in the earth’s orbital geometry are the fundamental cause of the succession of Quaternary ice ages.”
Three indices of global climate have been monitored in the record of the past 450,000 years in Southern Hemisphere ocean-floor sediments. 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
Glacial Cycles
History of Discovery

- Agassiz announces glacial theory
- Evidence of multiple ice ages discovered in Illinois
- Fourier
- Milankovitch explains glacial cycles
- Croll explains glacial cycles
- Humboldt debunks Adhemar
- Adhemar explains glacial cycles
- Magnetic reversals discovered
- Climate fluctuations found in ocean cores
- 18O theory developed
- Paleomagnetic time scale developed
- Hays, et al
- Evidence of multiple ice ages discovered in Illinois
- Church of Saint Sulpice, Paris

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Next Week