An Introduction to Milankovitch Cycles

Richard McGehee

Seminar on the Mathematics of Climate Change
School of Mathematics
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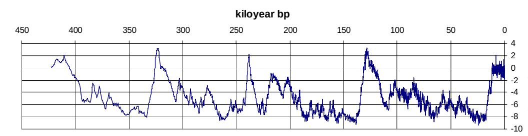
http://www.tqnyc.org/NYC052141/beginningpage.html

Milankovitch Cycles

What Causes Glacial Cycles?



Note the period of about 100 kyr.

Can you spot a cycle of 41 kyr?

Milankovitch Cycles

What Causes Glacial Cycles?

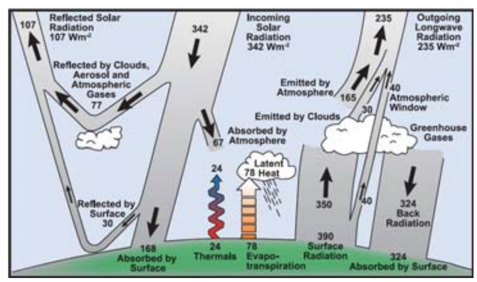
Popular Hypothesis

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.

Milankovitch Cycles

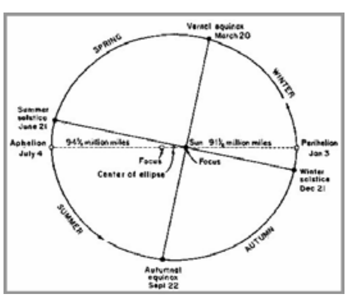
Heat Balance



Historical Overview of Climate Change Science, IPCC AR4, p.96
http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_CH01.pdf

Milankovitch Cycles

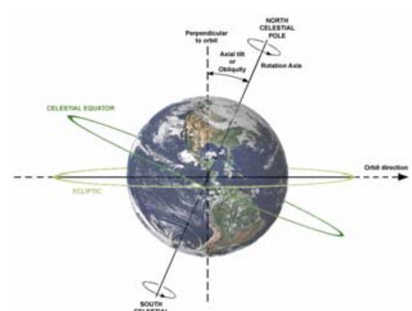
Eccentricity



http://www.crrel.usace.army.mil/permafrosttunnel/Ice_Age_Earth_Orbit.jpg

Milankovitch Cycles

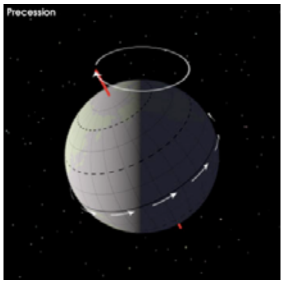
Obliquity



http://upload.wikimedia.org/wikipedia/commons/6/61/AxialTiltObliquity.png

Milankovitch Cycles

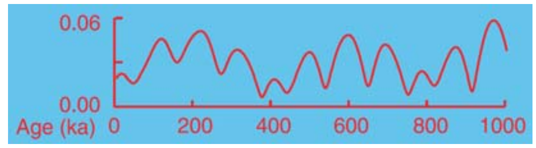
Precession



http://earthobservatory.nasa.gov/Library/Giants/Milankovitch/milankovitch_2.html

Milankovitch Cycles

Eccentricity



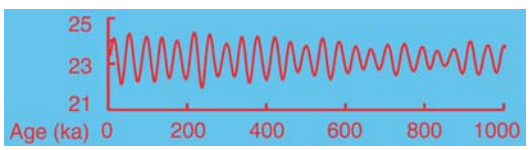
Note periods of about 100 kyr and 400 kyr.

Recall that glacial cycles have a period of about 100 kyr.

Zachos, et al, "Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present". ***Science*** **292** (2001)**, 687.**

Milankovitch Cycles

Obliquity

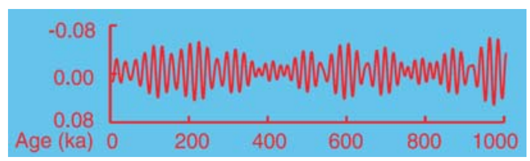


Note period of about 41 kyr.

Zachos, et al, "Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present". ***Science*** **292** (2001)**, 687.**

Milankovitch Cycles

Precession

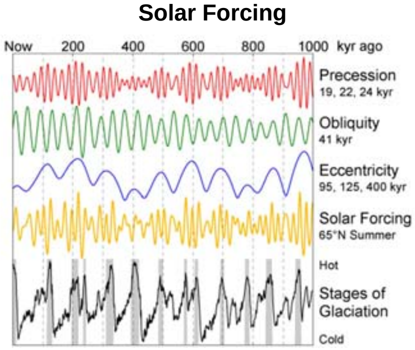


Note period of about 23 kyr.

Zachos, et al, "Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present". ***Science*** **292** (2001)**, 687.**

Milankovitch Cycles

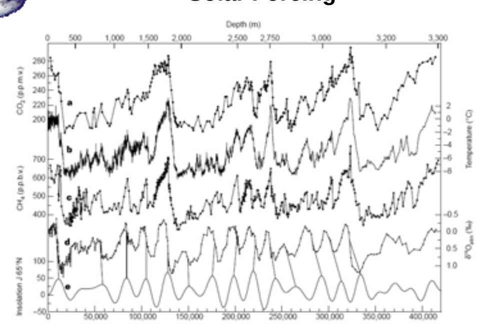
Solar Forcing



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

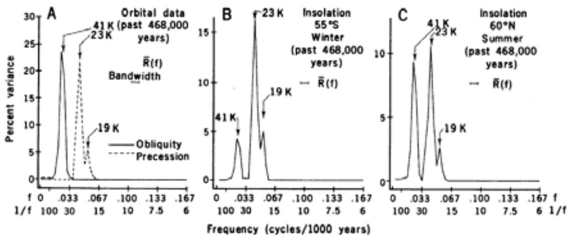
Milankovitch Cycles

Solar Forcing



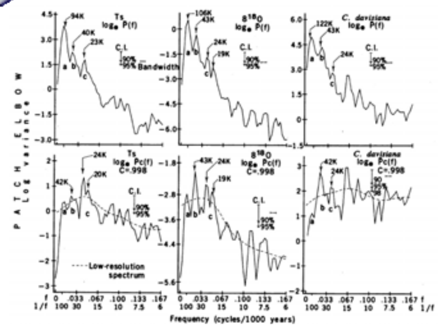
Petit, *et al*, *Nature* **399** (1999), p. 431

Milankovitch Cycles
Solar Forcing (Hays, et al)



Hays, *et al*, *Science* **194** (1976), p. 1125

Milankovitch Cycles
Climate Response, Hays, et al



Hays, *et al*, *Science* **194** (1976), p. 1127

Milankovitch Cycles
Hays, et al, Summary

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.

Hays, *et al*, *Science* **194** (1976), p. 1131

Milankovitch Cycles
Hays, et al, Summary

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.

Hays, *et al*, *Science* **194** (1976), p. 1131

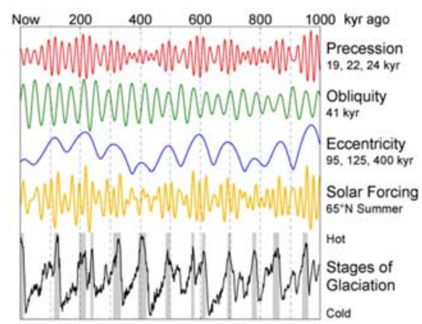
Milankovitch Cycles
Hays, et al, Summary

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.

Hays, *et al*, *Science* **194** (1976), p. 1131

Milankovitch Cycles
Solar Forcing



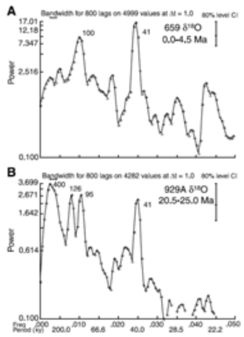
http://en.wikipedia.org/wiki/Milankovitch_cycles

Milankovitch Cycles

Climate Response (Zachos, et al)

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

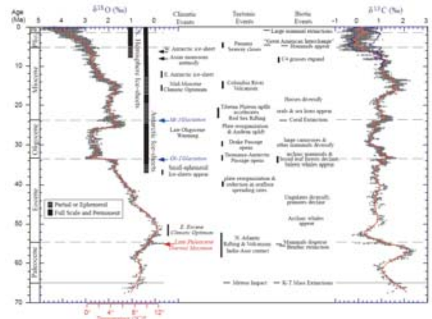
B. Power spectrum of climate for the period 25 Myr bp to 20.5 Myr bp. Note the new peak at 400 Kyr and the "split" peaks at 126Kyr and 95 Kyr.



Zachos, *et al*, *Science* **292** (2001), p. 689

Milankovitch Cycles

Recent History



Zachos, *et al*, *Science* **292** (2001), p. 689

Milankovitch Cycles

Milankovitch Cycles are Insufficient

Rind, et al, used a global circulation model to try to predict the last ice age using the Milankovitch insolation data. It failed:

"The results show that the model fails to maintain snow cover through the summer at locations of suspected initiation of the major ice sheets, despite the reduced summer and fall insolation."

"The experiments indicate there is a wide discrepancy between the model's response to Milankovitch perturbations and the geophysical evidence of ice sheet initiation."

Rind, *et al*, *J. Geophysical Research* **94** (1989), p. 12851

Milankovitch Cycles

Milankovitch Cycles are Insufficient

Rind, continued.

"If the model results are correct, it indicates that the growth of ice occurred in an extremely ablative environment, and thus demanded some complicated strategy, or else some other climate forcing occurred in addition to the orbital variation influence (and CO2 reduction), which would imply we do not really understand the cause of the ice ages and the Milankovitch connection. If the model is not nearly sensitive enough to climate forcing, it could have implications for projections of future climate change."

Rind, *et al*, *J. Geophysical Research* **94** (1989), p. 12851

Milankovitch Cycles

Some Remarks

Why focus on eccentricity?

Solar intensity at distance r from the sun:

$$Q(t) = \frac{k_1}{r(t)^2}$$

Angular momentum:

$$\Omega = r^2\dot{\theta}$$

$$Q(t) = \frac{k_1\dot{\theta}}{\Omega}$$

Mean annual solar input (T = one year):

$$\bar{Q} = \frac{1}{T}\int_0^T Q(t)\,dt = \frac{k}{T\Omega}\int_0^T \dot{\theta}\,dt = \frac{2\pi k_1}{T\Omega}$$

Milankovitch Cycles

Some Remarks

Why focus on eccentricity?

Total Energy:

$$\frac{1}{2}|v|^2 - \frac{1}{r(t)} = h$$

Kepler's Third Law:

$$T = k_2|h|^{-3/2}$$

Mean annual solar input:

$$\bar{Q} = \frac{k_3|h|^{3/2}}{\Omega}$$

More relevant question: How does $|h|^{3/2}\Omega^{-1}$ vary over geologic time?

Milankovitch Cycles

Some Remarks

Recall Budyko's model:

$$\kappa \dot{T} = \boxed{\bar{Q}s(y)}\left(1-\alpha(T)(y)\right) - I(T)(y) + H(T)(y)$$

The annual average insolation as a function of latitude θ, where $y = \sin\theta$, is

$$\bar{Q}s(y)$$

Even more relevant question: How does this function vary over geologic time?