Milankovitch Theory

- Milankovitch Theory: Climate change due to variations in the earth's orbit

The changes of orbital geometry

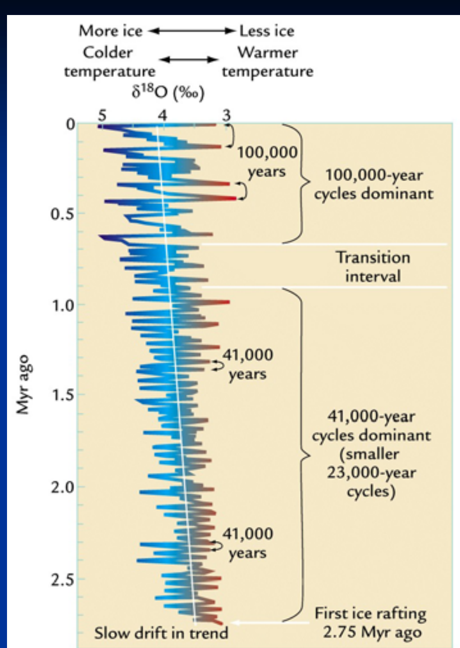
↓

The changes of distribution of Insolation S(latitude, time)

↓

Climate Changes

Amplified or Reduced?



Evidence of ice sheet evolution during last 2.5 million years. North Atlantic sediment core $\delta^{18}O$. The development of the ~100,000 year cycles of glaciation is a relatively recent phenomena (600,000 years). From M. E. Raymo, Ann. Rev. of Earth and Planetary Science, 22, 353, 1994. Figure from Ruddiman.

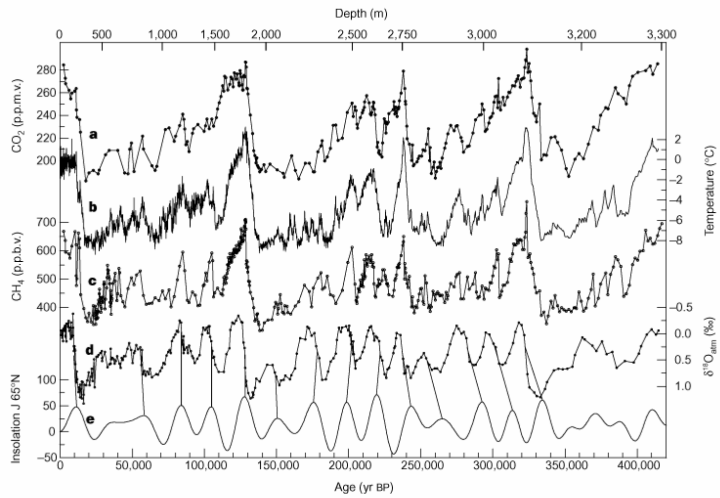


Figure 3 Vostok time series and insolation. Series with respect to time (GT4 timescale for ice on the lower axis, with indication of corresponding depths on the top axis) of: **a**, CO_2; **b**, isotopic temperature of the atmosphere (see text); **c**, CH_4; **d**, $\delta^{18}O_{atm}$; and **e**, mid-June insolation at 65° N (in $W m^{-2}$) (ref. 3). CO_2 and CH_4 measurements have been performed using the methods and analytical procedures previously described[5,9]. However, the CO_2 measuring system has been slightly modified in order to increase the sensitivity of the CO_2 detection. The thermal conductivity chromatographic detector has been replaced by a flame ionization detector which measures CO_2 after its transformation into CH_4. The mean resolution of the CO_2 (CH_4) profile is about 1,500 (950) years. It goes up to about 6,000 years for CO_2 in the fractured zones and in the bottom part of the record, whereas the CH_4 time resolution ranges between a few tens of years to 4,500 years. The overall accuracy for CH_4 and CO_2 measurements are ±20 p.p.b.v. and 2–3 p.p.m.v., respectively. No gravitational correction has been applied.

Hays, Imbrie, and Shackleton
Science, 194, 1121, 1976
Variations in the Earth's Orbit: Pacemaker of the Ice Ages

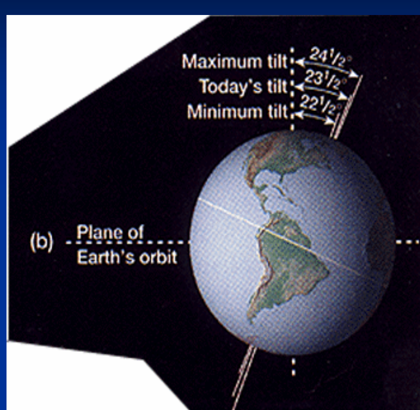
- "It is concluded that changes in the earth's orbital geometry are fundamental causes of the succession of Quarternary ice ages."
- "The dominant, 100,000-year climatic component has an average period close to, and ins in phase with, orbital eccentricity. Unlike the correlations between climate and 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 non-linearity."

Review: Orbital Parameters

- Two parameters to describe orbit
  - **Radius**: how far away from the sun⇒ annual-mean insolation
  - **Eccentricity** : how elliptical the orbit is ⇒ annual-mean insolation
- Two parameters to describe the orientation of the planet with respect to the solar orbit
  - **Obliquity** : how the planet tilts ⇒ annual-mean equator-to-pole gradient of insolation
  - **Precession** : how the planet wobbles ⇒ seasonal insolation

Obliquity

Precession



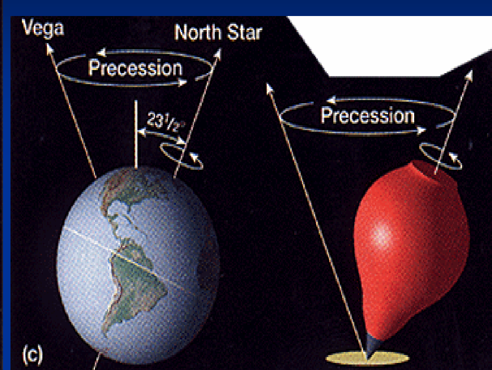
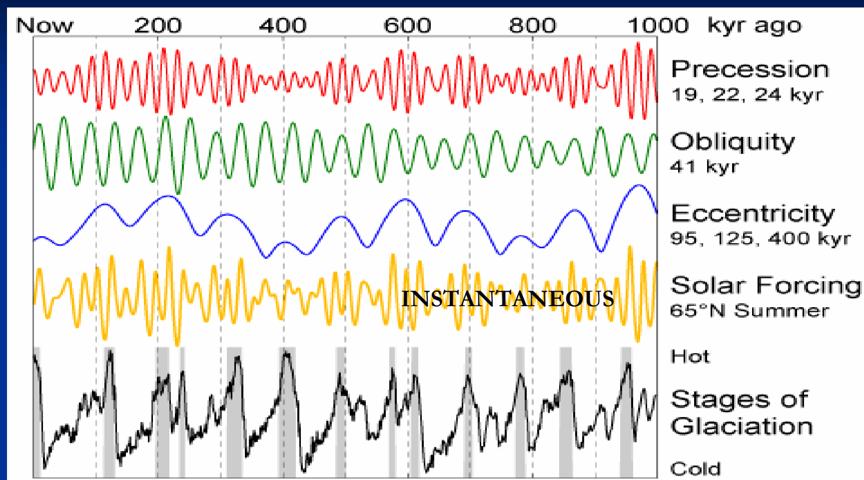
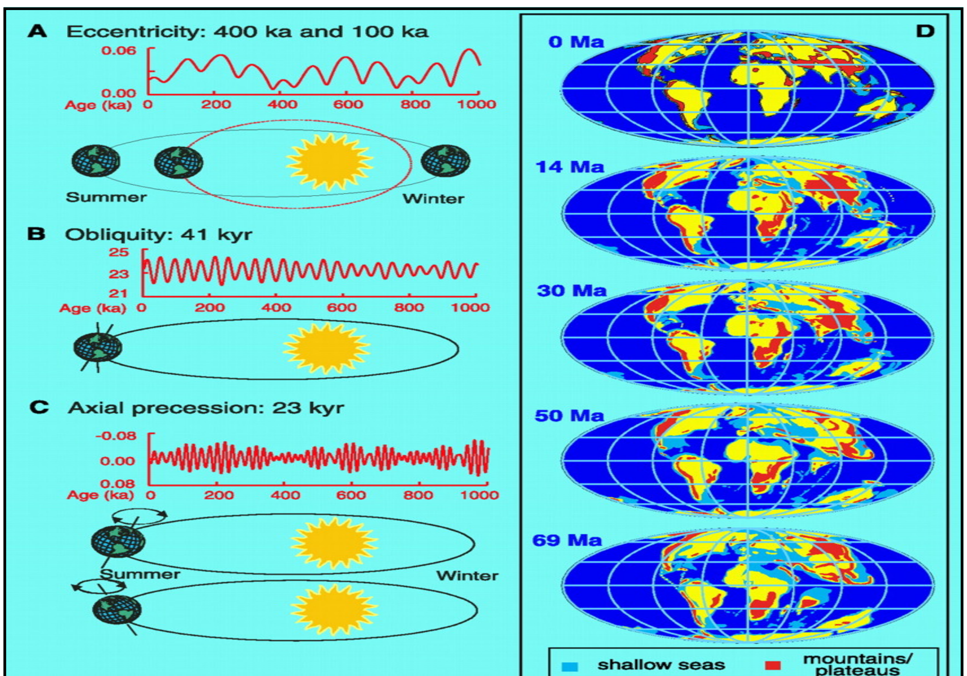


image adopted from The Atmosphere by Lutgens and Tarbuck, © 1998 by Prentice-Hall, Inc





Zachos et al., Science, 2001

Eccentricity Cycle

- It takes about 100k years to complete this cycle (superimposed 400k-yr cycle) Figure 11.11
- The annual-mean insolation $\propto (1- e^2)^{-1/2}$

  $e_{max} \sim 0.05$, $e_{min} \sim 0.01$, $S_{max}-S_{min}=0.125\%S_{max}$
- Currently, we are in an orbit of low eccentricity $e=0.015$ (near circular)
  - Perihelion/Aphelion : current around Jan.3/Jul.4

Precession Cycle

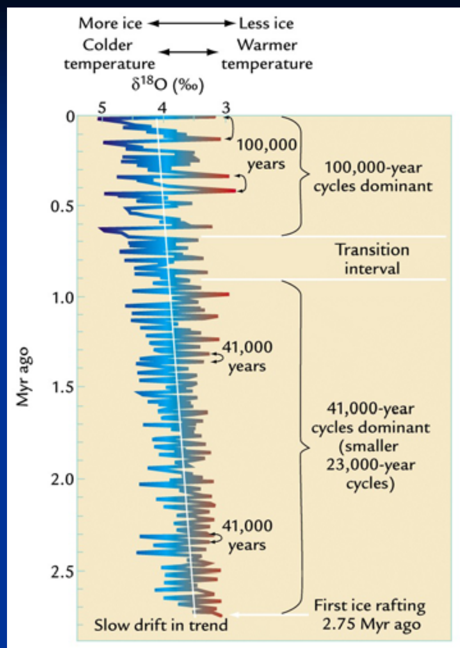
- The earth is wobbling: a spinning top
- It takes around **23,000** year to make one cycle (Figure 11.12), season switching
- Modulating *instantaneous* insolation, ~20% changes in high-latitude summer insolation
- Very little change in summer energy, however (Huybers, 2006).

Summer Insolation
Summer Energy

- Huybers, 2006: Although insolation intensity (the instantaneous energy) is modulated significantly by precession, the insolation energy (the total energy received during summer) is not. This can be understood by noting that $I \propto 1/r^2$, where I is insolation intensity and r is the distance from the Earth to the Sun. Conservation of angular momentum (Kepler's second law) dictates that $dt \propto r^2 d\lambda$, where dt is an infinitesimal change in time and $d\lambda$ the corresponding change in solar longitude. The summer energy received by the Earth is then $J = Idt \propto d\lambda$. In contrast with I, the J between any two solar longitudes is independent of r and, thus, independent of the precession of the equinoxes.
- e.g. today: Solar intensity is higher in the Southern Hemisphere during summer, but the summer is shorter.

Testing the Milankovitch Theory

- Basic idea:
  - Lower insolation in summer/snow covered in the fall/perennial icecover expand
  - Higher insolation in winter/higher temperature/more water vapor in the air/more precipitation/greater snow accumulation
- Use dated climate proxies to test the spectral power at the orbital frequencies. Use phase information to test for consistency. Difficult because of dating!



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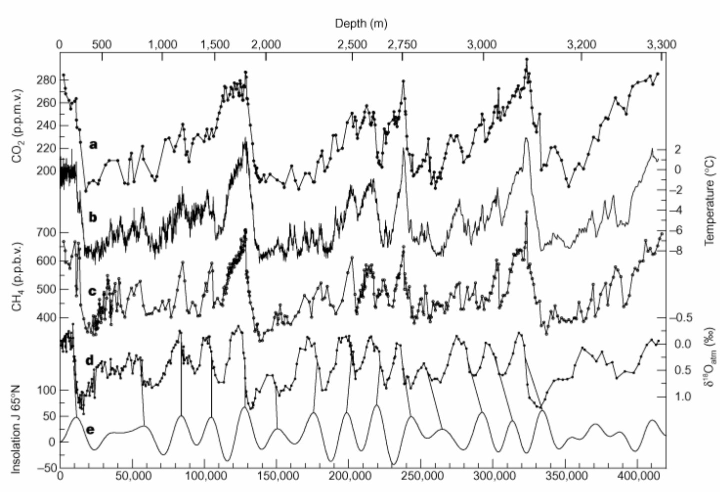


Figure 3 Vostok time series and insolation. Series with respect to time (GT4 timescale for ice on the lower axis, with indication of corresponding depths on the top axis) of: **a**, CO_2; **b**, isotopic temperature of the atmosphere (see text); **c**, CH_4; **d**, $\delta^{18}O_{atm}$; and **e**, mid-June insolation at 65° N (in $W m^{-2}$) (ref. 3). CO_2 and CH_4 measurements have been performed using the methods and analytical procedures previously described[5,9]. However, the CO_2 measuring system has been slightly modified in order to increase the sensitivity of the CO_2 detection. The thermal conductivity chromatographic detector has been replaced by a flame ionization detector which measures CO_2 after its transformation into CH_4. The mean resolution of the CO_2 (CH_4) profile is about 1,500 (950) years. It goes up to about 6,000 years for CO_2 in the fractured zones and in the bottom part of the record, whereas the CH_4 time resolution ranges between a few tens of years to 4,500 years. The overall accuracy for CH_4 and CO_2 measurements are ±20 p.p.b.v. and 2–3 p.p.m.v., respectively. No gravitational correction has been applied.

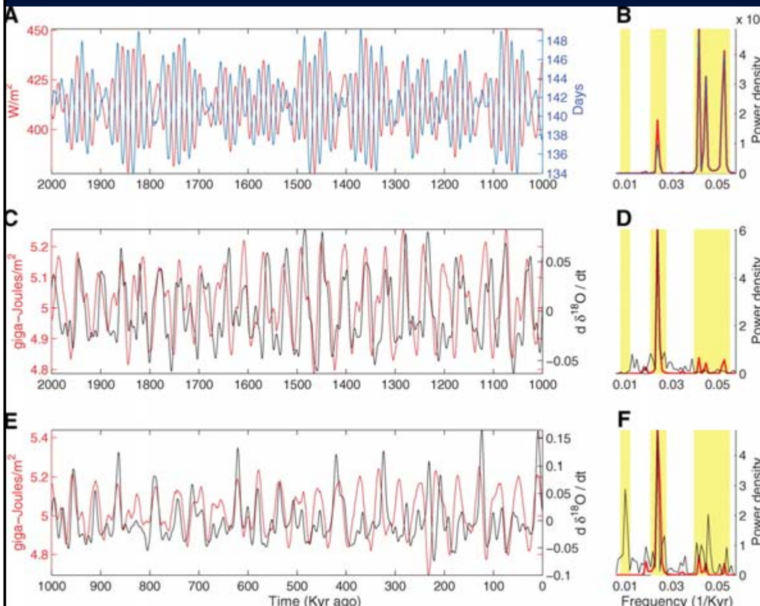
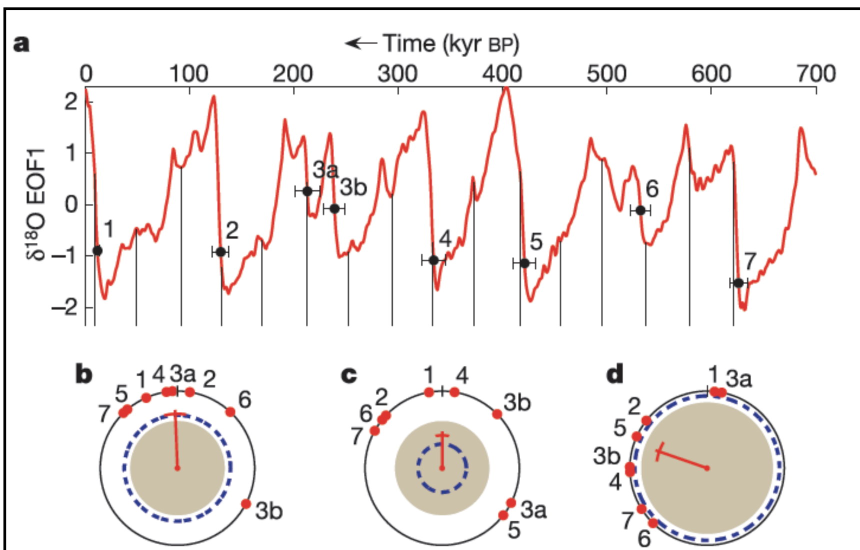


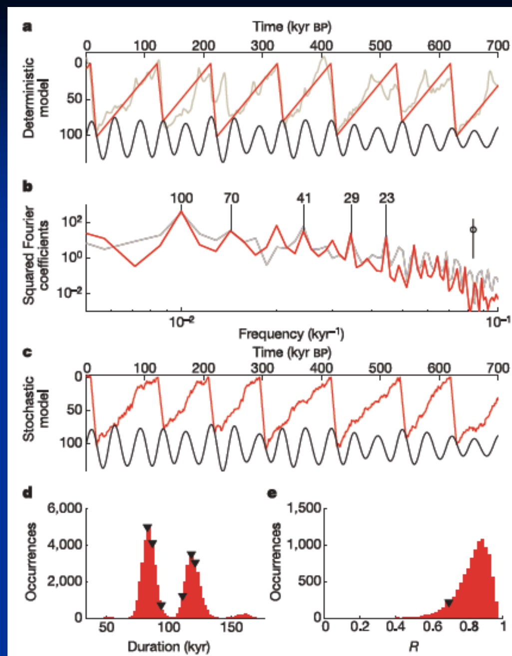
Fig. 2. Insolation forcing and Pleistocene glacial variability. (**A**) Number of days that insolation is above 275 W/m2 (blue) and the average insolation intensity during this interval (red). Intensity and duration are anticorrelated. (**B**) Spectral estimate of the duration (blue) and intensity (red), showing that the majority of the variability is at the precession periods. Shaded bands from left to right indicate the 100-ky, 41-ky (obliquity), and 21-ky (precession) bands. (**C**) Summer energy (red) and the time rate of change of 18O (black) for the early Pleistocene and (**D**) the corresponding spectral estimates. Positive rates of change indicate decreasing ice volume. Variability in both records is predominantly at the 41-ky obliquity period. (**E** and **F**) Same as (C) and (D) but for the late Pleistocene. The time rate of change of 18O has variability at the 100-ky period not present in the forcing.

Huybers, Science 2006



a, [18]O EOF1 normalized so that negative values indicate more ice. Dots indicate onset of a termination and horizontal bars indicate one-standard-deviation age-model uncertainties[13]. Termination 3 is split between events 3a and 3b. Vertical lines indicate the time of maxima in obliquity. Note that time runs from right to left in the palaeoclimate convention. **b**, The obliquity phase (dots) sampled at each termination and plotted on a unit circle. The vector average has a magnitude $R = 0.70$ (cross mark) exceeding the critical value $c = 0.60$ (filled circle), so that H_0 is rejected. Furthermore, R is near H_1's maximum-likelihood value (dashed circle). The direction is indistinguishable from maximum obliquity (top of the circle). **c**, **d**, Analogous tests are made for precession ($R = 0.43$, $c = 0.60$) (**c**) and eccentricity ($R = 0.66$, $c = 0.84$) (**d**), but in neither case can the corresponding H_0 be rejected. See the Supplementary Information for more details.

Obliquity pacing of the late Pleistocene glacial terminations



a, Deterministic model results (red) with an obliquity-dependent threshold (black) plotted over EOF1 (brown). **b,** Periodograms of the deterministic model results (red) and EOF1 (brown). Concentrations of energy are centred on the 1/41-kyr obliquity frequency and the 1/100-kyr glacial band; as well as combination tones at 1/70, 1/29 and 1/23 kyr. The approximate 95% confidence interval is indicated by the vertical bar on the right. **c,** A realization of the stochastic model. **d,** Histogram of the time between terminations, derived from many runs of the stochastic model. The observed duration between terminations (triangles, using termination 3a not 3b) coincide with the dominant 80- and 120-kyr modes. **e,** Histogram of Rayleigh's *R* from the stochastic model with the observed obliquity value, *R* = 0.70, indicated by the triangle.

Obliquity pacing of the late Pleistocene glacial terminations
Peter Huybers and Carl Wunsch
Nature 434, 491-494 (24 March 2005)
doi: 10.1038/nature03401

Possible mechanisms for ~100 Kyr power

- Stochastic resonance (**phase locking** to eccentricity) is attractive in mathematics. But what's the physics interpretation of the stochastic noise.
- **Positive feedback** inside climate system to amplify weak solar signal? Are larger ice sheets inherently more unstable (Schoof and hydrostatics of the crust)? What is the role of the ocean?
- **Carbon.** Why does CO_2 have such a stronger ~100KYr peak than does sea ice? Next.

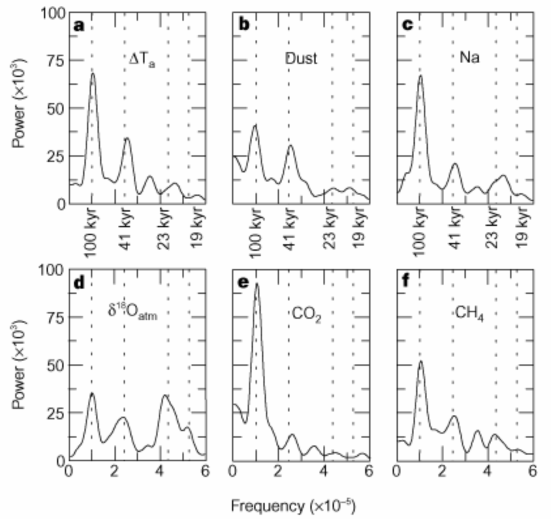


Figure 4 Spectral properties of the Vostok time series. Frequency distribution (in cycles yr^{-1}) of the normalized variance power spectrum (arbitrary units). Spectral analysis was done using the Blackman-Tukey method (calculations were performed with the Analyseries software[47]): **a**, isotopic temperature; **b**, dust; **c**, sodium; **d**, $\delta^{18}O_{atm}$; **e**, CO_2; and **f**, CH_4. Vertical lines correspond to periodicities of 100, 41, 23 and 19 kyr.

Enigmas of solar forcing

"Among the most intriguing enigmas of the climate system is that on the one hand, the Earth's climate appears to be exquisitely sensitive to relatively minor variations in the distribution of insolation owing to orbital variations, but on the other hand, it is in a grosser sense stable, in that it has varied only moderately in response to a roughly 30% increase in solar insolation over the life of the planet." *Kerry Emanuel (JGR 107, D9, ACL4)*

Faint Young Sun Problem

Sensitivity to the eccentricity cycle?