The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
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SMR/1884-2

Conference on Milankovitch cycles over the past 5 million years

22 - 24 March 2007

Milankovitch Hypotheses

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Milankovitch Hypotheses

Carl Wunsch
Trieste, March 2007

Ice volume changes through time are one of the most dramatic of all climate signals. Without an explanation, in particular, of the approximately 40,000 year and 100,000 year variations, it is difficult to maintain that the climate system is understood.

What is the nature of observed climate change?

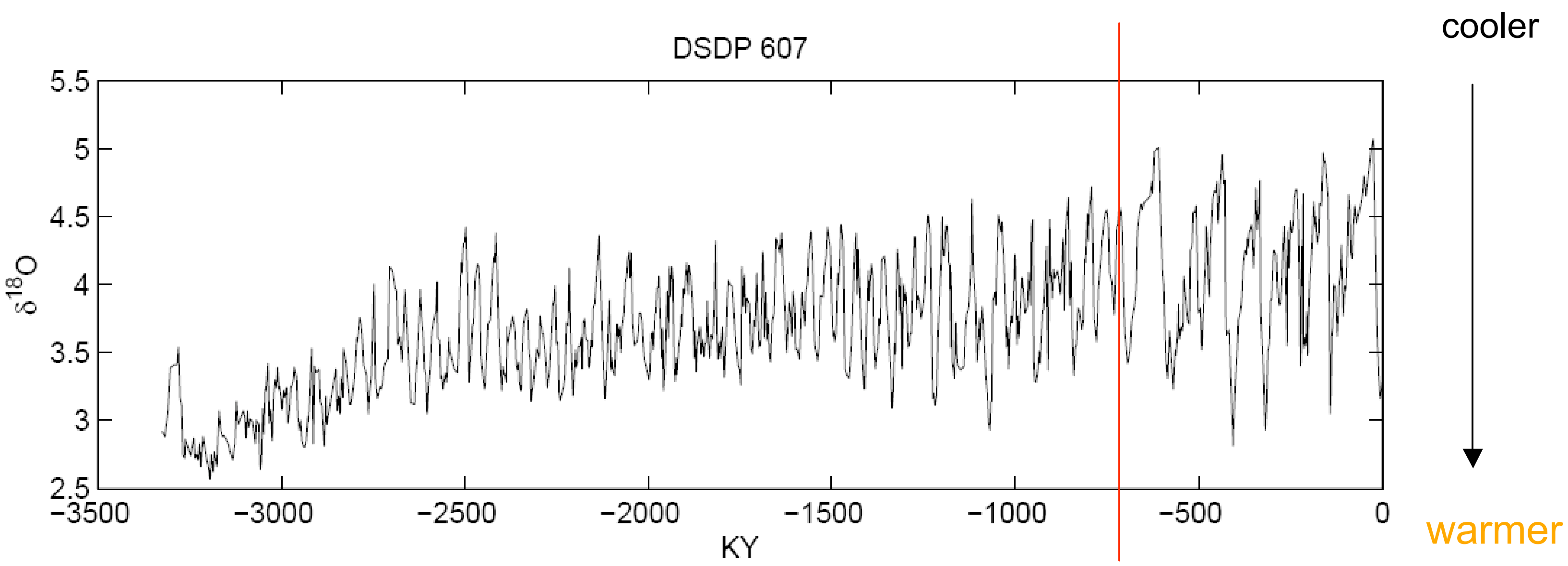
Is it periodic? Or at least deterministic? Is it controlled by orbital influences? How can we tell?

How much of what we see is definitely attributable to known causes?

Can one predict the time of onset of a new ice age (with and without anthropogenic interference)?

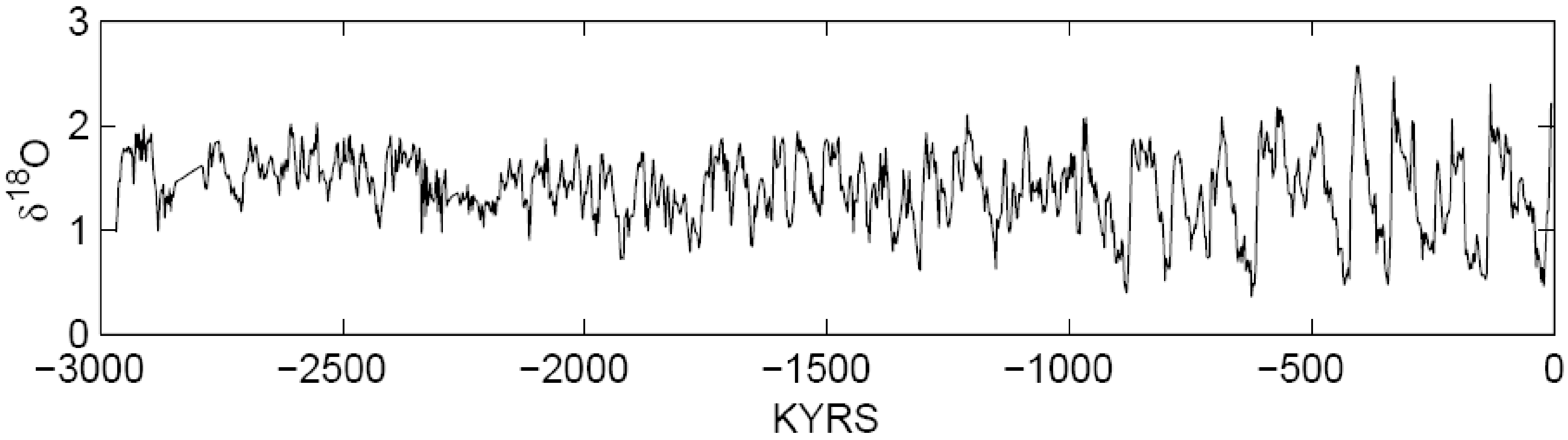
The story of ice ages starts with terrestrial geology: Adhémar, Agassiz and others.

Much of what we know today comes from cores---those from the seafloor and from the Greenland and Antarctic ice caps.

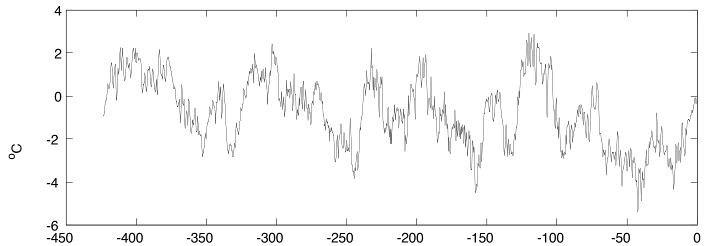


from floor of the subpolar N. Atlantic. Raymo & Nisancioglu (2003)

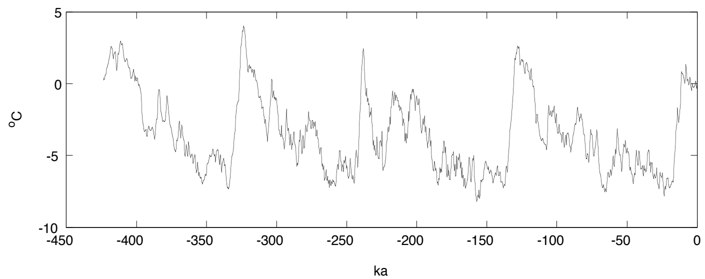
Note change in character about -800,000y



Tiedemann et al. (1994) ODP659 SE N. Atlantic. *Tuned* core.



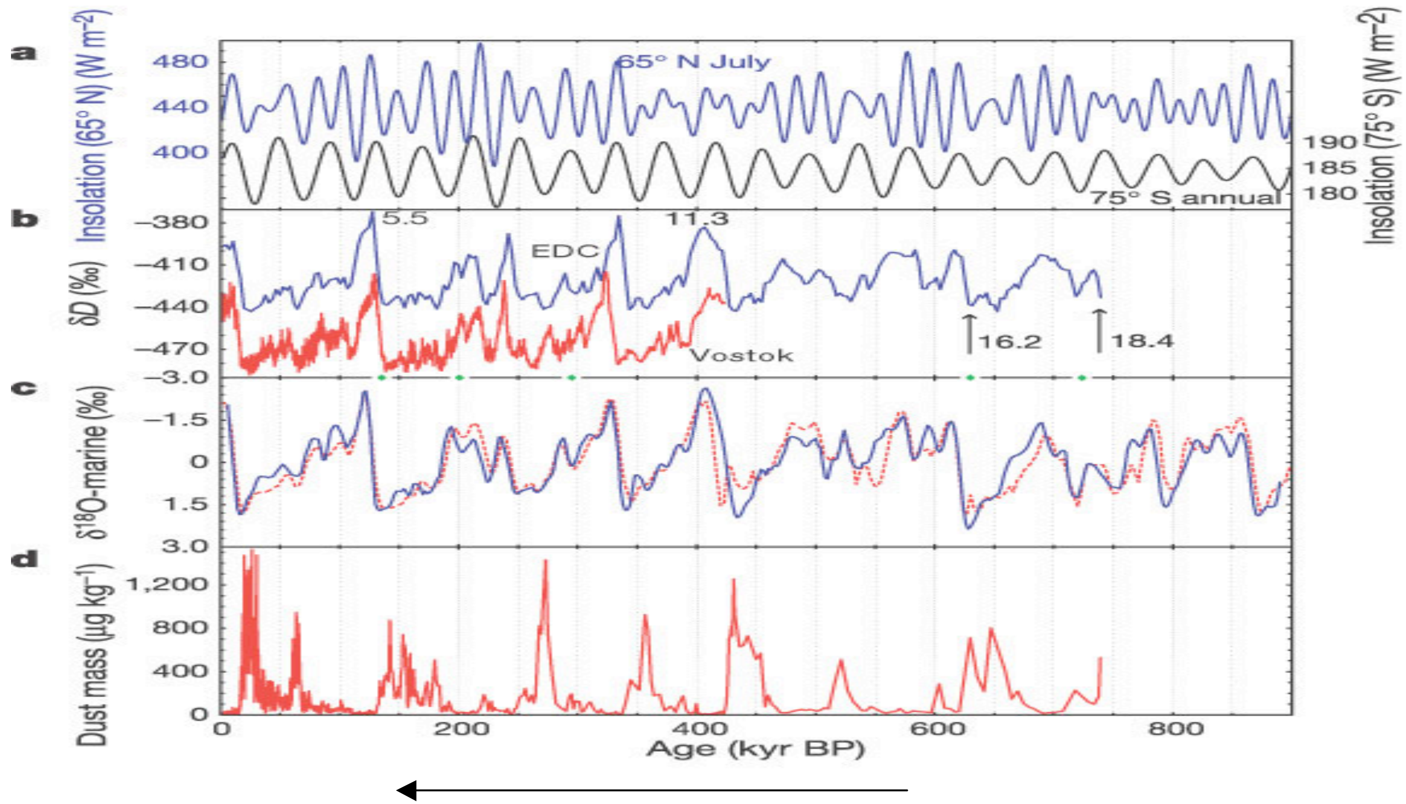
Vostok ice core Vimieux et al., 2002
"source temperature"



"site temperature"

Ice Cores

EPICA Community Members, Nature, 2004: Greenland.



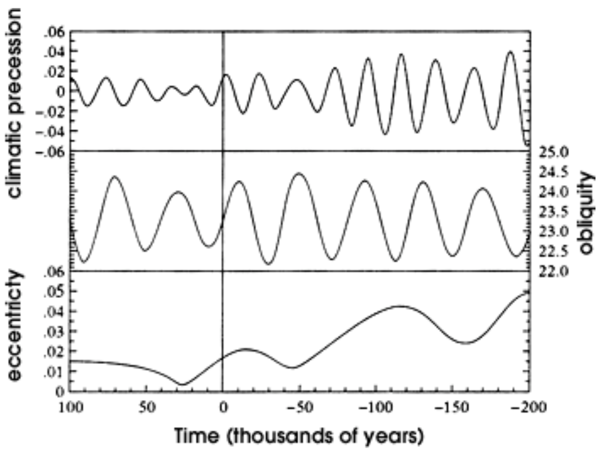
Note backward running time and specific insolation curves. *Nothing* is periodic.

The astronomical story apparently begins with J.A. Adhémar (c.1842) and James Croll (c.1875). Refined and completed by M. Milankovitch in the early 20th century.

The modern story largely begins with a paper by Hays, Imbrie and Shackleton, Science, 1976.

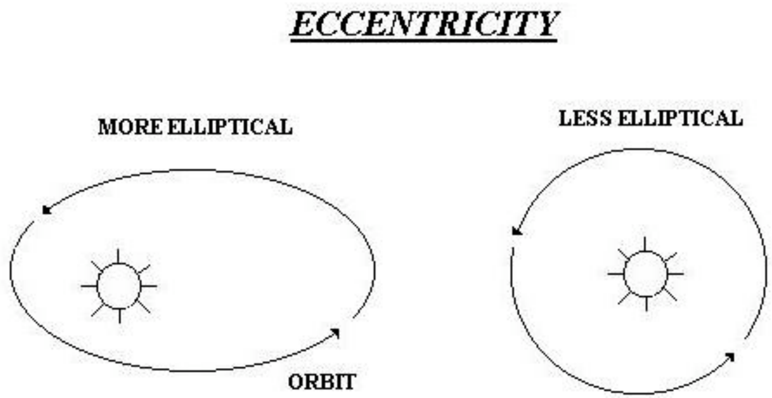
Why does one fix on astronomical control? The search for causality.

Has been known for a long time that there are several elements of the earth's orbit about the sun that change the distribution of insolation (incoming radiation) through time: eccentricity of the orbit; change in obliquity; precession of the equinoxes. (So do the diurnal and annual cycles!)

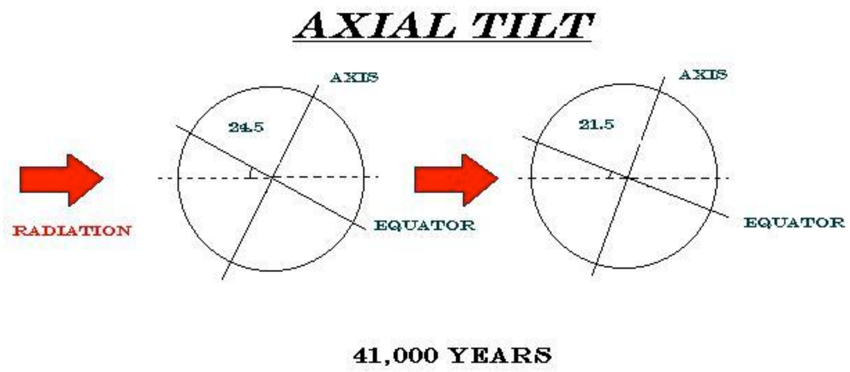


http://earthobservatory.nasa.gov/Library/Giants/Milankovitch/

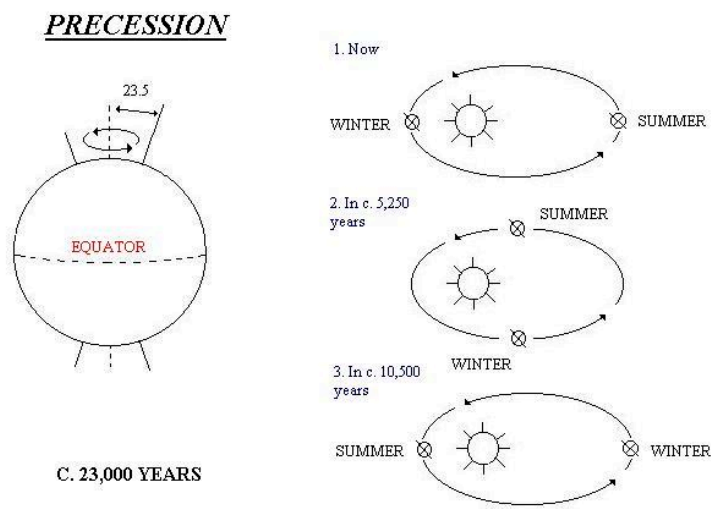
Gravitational solar tides and insolation forcing (Milankovitch forcing) can be derived together systematically. Conventional tidal frequencies are the high frequency limit of Milankovitch forcing (usually ignored) and Milankovitch forcing frequencies are the low-frequency limit of the gravitational tides (usually ignored). Because atmospheric tides are primarily thermal, and there is a measurable oceanic thermal forcing response, makes sense to discuss them together (see also, Munk and Bills, J. Phys. Oc., 2007).



Time scales: 400,000,
100,000yrs.

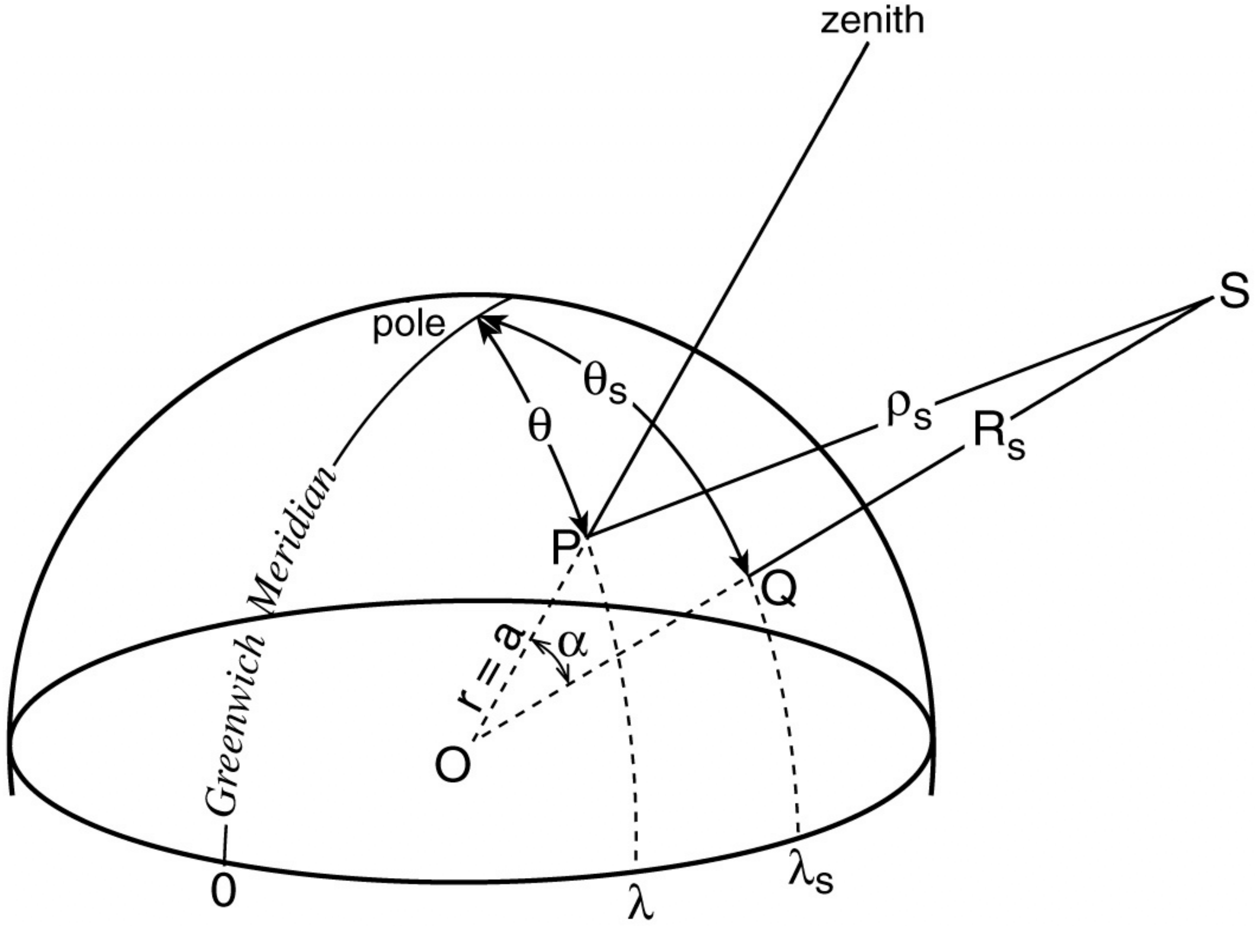


symmetric about equator



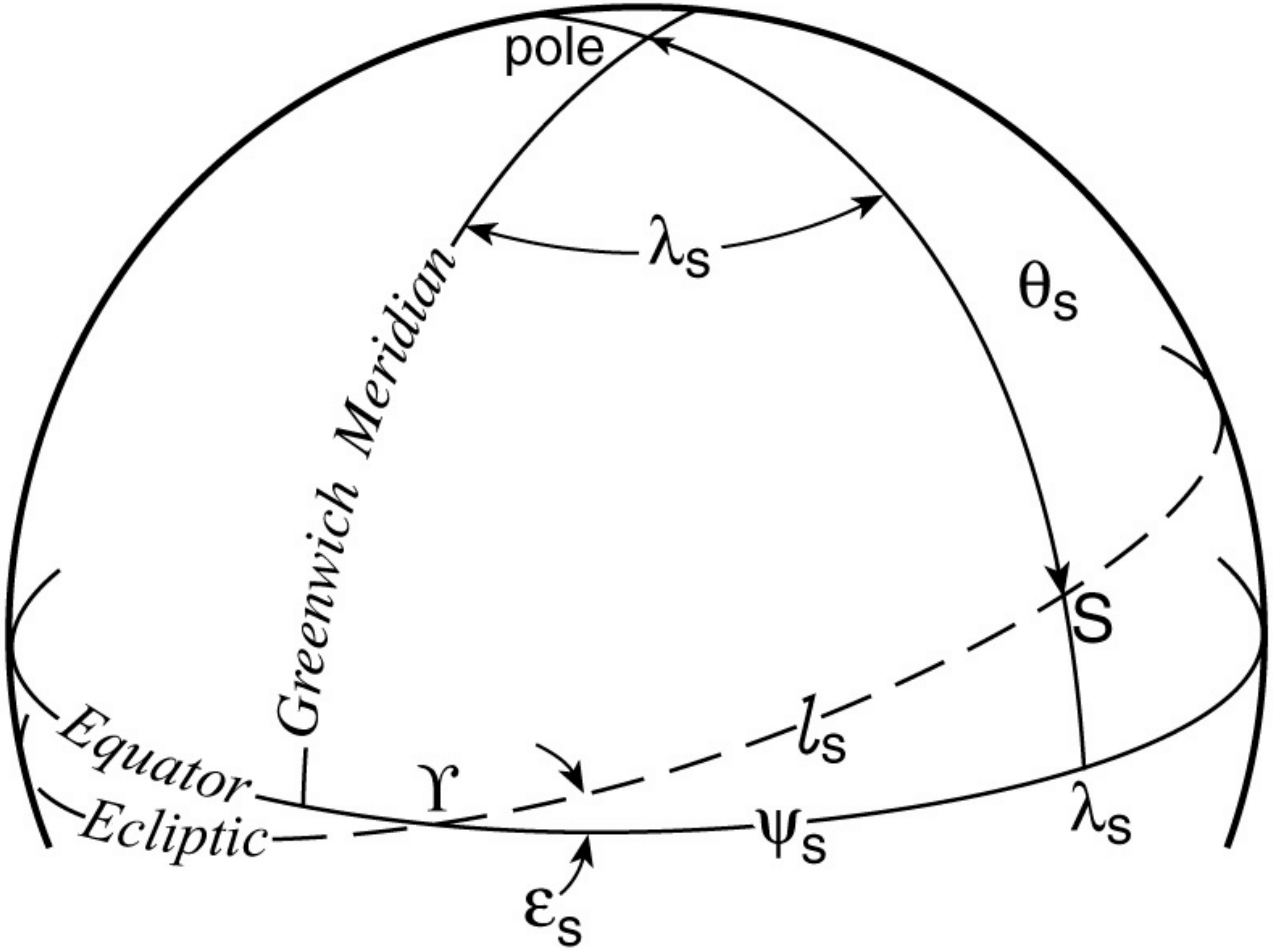
antisymmetric about equator

modified from Wikipedia, 2006



$$V_S = \frac{GM_S}{\rho_S} = \frac{GM_S}{R_S\left(1 - 2(r/R_S)\cos\alpha + (r/R_S)^2\right)^{1/2}}.$$

tidal attraction



pole
λs
θs
Greenwich Meridian
S
Equator
ls
ϒ
λs
Ecliptic
ψs
εs

Gravitational Forcing

$$V_S = \frac{GM_S}{R_S} \sum_{n=0}^{\infty} \left(\frac{r}{R} \right)^n P_n(\cos\alpha) =$$

$$\frac{GM_S}{R_S} \left(1 + \frac{r}{R_S} \cos\alpha + \left(\frac{r}{R_S} \right)^2 \left[\frac{3}{2} \cos^2\alpha - \frac{1}{2} \right] + \ldots \right.$$

$$\cos\alpha = \cos\theta_S \cos\theta + \sin\theta_S \sin\theta \cos(\lambda_S - \lambda)$$

(convert into observer's colatitude and longitude)

$$\frac{V_S}{g} = \frac{3}{2} H \left(\cos^2\theta_S - \frac{1}{3} \right) \left(\cos^2\theta - \frac{1}{3} \right) -$$

$$\frac{1}{2} H \sin(2\theta_S) \sin(2\theta) \cos(\lambda_S - \lambda)$$

$$+ \frac{1}{2} H \sin^2\theta_S \sin^2\theta \cos 2(\lambda_S - \lambda) + \ldots,$$

$$H = \frac{3}{2} \frac{M_S}{M_E} \left(\frac{a}{R_S} \right)^3 .$$

Label	Name	Frequency (°/mean solar day)	Period (tropical years)
f_1	1 cycle/lunar day	347.81	2.83×10^{-3}
f_2	1 cycle/tropical month	13.18	7.47×10^{-2}
f_3	1 cycle/tropical year	0.986	1.0
f_4	1 cycle/lunar perigee period	0.1114	8.98
f_5	1 cycle/lunar nodal period	0.0529	18.63
f_6	1 cycle/solar perigee period	4.71×10^{-5}	20,940

“Perigee period” corresponds to what the climate community calls the “precession band”, and is the point of overlap of the conventional tidal and insolation developments. Tidal development includes lunar components which are not directly relevant to insolation.

Insolation forcing:

$$\begin{aligned}\mathcal{R} &= S_0\left(\frac{\bar{R}_S}{\rho_S}\right)\cos\alpha \\ &= S_0\frac{\bar{R}_S\cos\alpha}{R_S\left(1-2\left(a/R_S\right)\cos\alpha+\left(a/R_S\right)^2\right)^{1/2}},\ \cos\alpha>0 \\ &= 0,\ \cos\alpha<0\end{aligned}$$

(day/night difference taken as abrupt)

$$\begin{aligned}\mathcal{R} &= S_0\frac{\bar{R}_S}{R_S}\cos\alpha\left(1+\frac{a}{R_S}P_1\left(\cos\alpha\right)+\left(\frac{a}{R_S}\right)^2P_2\left(\cos\alpha\right)+...\right),\ \cos\alpha>0 \\ &= 0,\ \cos\alpha<0.\end{aligned}$$

$$\frac{\mathcal{R}}{S_0}=\frac{\bar{R}_S}{R_S}\left\{\frac{\cos\alpha}{2}+\sum_{n=2,4,6,...}\frac{2n+1}{2}\left[\frac{1(-1)..(3-n)}{2\left(4\right)...\left(2+n\right)}\right]P_n\left(\cos\alpha\right)\right\},\ 0\leq\alpha\leq\pi,$$

If omit all terms of frequencies greater than 5 cycles/tropical year:

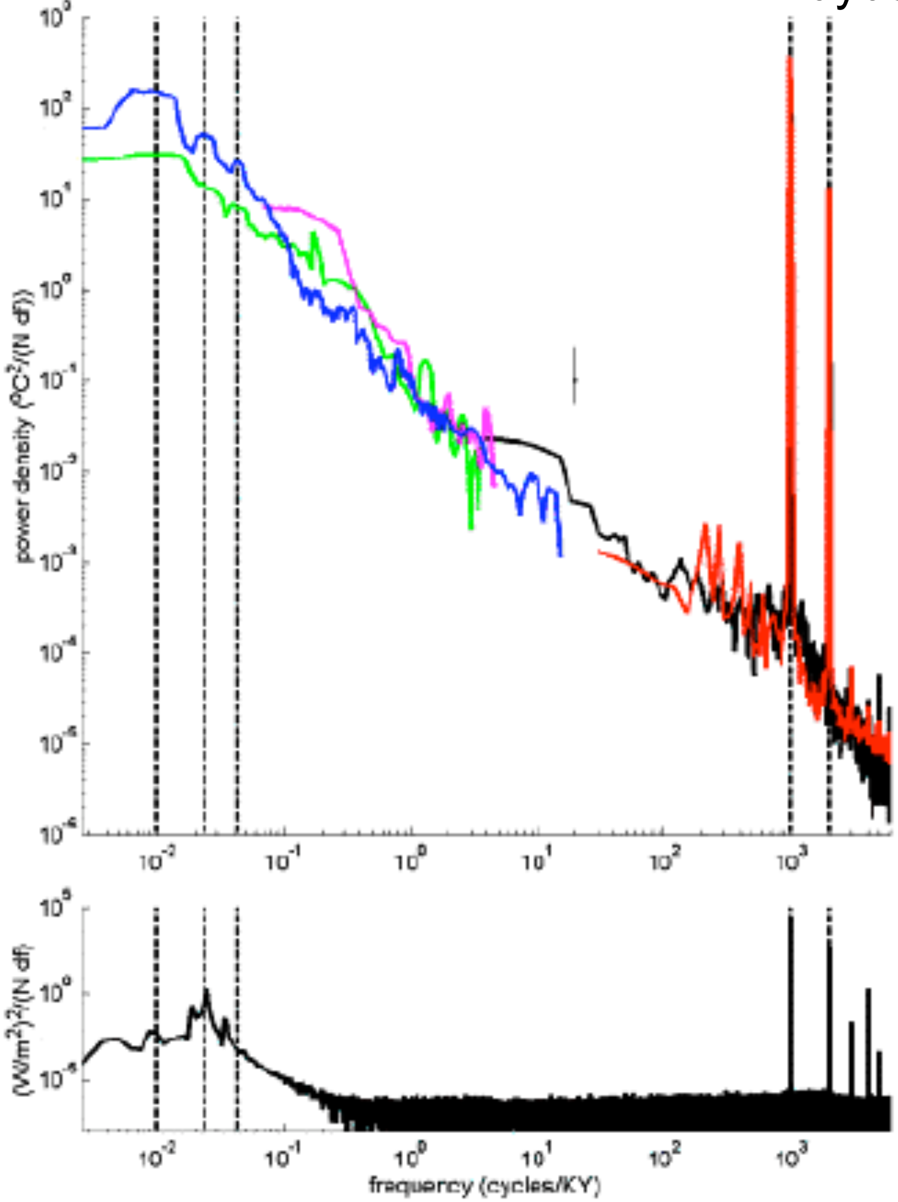
$$\frac{\mathcal{R}}{S} = \left(\frac{\bar{R}_S}{a_s}\right)^2 \left\{ \begin{array}{c} \frac{1}{4}P_0(\cos\theta)\left[1+\frac{e^2}{4}+2e\cos M+\frac{5}{2}e^2\cos 2M\right]+ \\ \frac{1}{2}P_1(\cos\theta)\left[\begin{array}{c}\left(1-\frac{e^2}{2}\right)\sin\varepsilon_S\sin(\omega+M)+2e\sin\varepsilon_S\sin(\omega+2M)+ \\ \frac{e^2}{8}\sin\varepsilon_S\sin(\omega-M)+\frac{27}{8}e^2\sin\varepsilon_S\sin(\omega+3M)\end{array}\right]+ \\ +\frac{5}{16}P_2(\cos\theta)\left[\begin{array}{c}\left(1+\frac{e^2}{2}\right)\left(\frac{3}{4}\sin^2\varepsilon_S-\frac{1}{2}\right)-\frac{3}{4}\left(1-\frac{7}{2}e^2\right)\sin^2\varepsilon_S\cos(2(\omega+M)) \\ +2e\left(\frac{3}{4}\sin^2\varepsilon_S-\frac{1}{2}\right)\cos M+\frac{3}{4}e\sin^2\varepsilon_S\cos(2\omega+M) \\ -\frac{9}{4}e\sin^2\varepsilon_S\cos(2\omega+3M)+\frac{5}{2}e^2\left(\frac{3}{4}\sin^2\varepsilon_S-\frac{1}{2}\right)\cos 2M \\ -\frac{39}{8}e^2\sin^2\varepsilon_S\cos(2\omega+4M)+\ldots\end{array}\right]\end{array}\right. \tag{25}$$

Averaging over a tropical year (Rubincam, 1994):

$$\left.\frac{\mathcal{R}}{S}\right|_{NS} = \left(\frac{\bar{R}_s}{a_s}\right)^2 \left\{\frac{1}{4}\left[1+\frac{e^2}{4}\right]+\frac{5}{16}P_2(\cos\theta)\left(1+\frac{e^2}{2}\right)\left(\frac{3}{4}\sin^2\varepsilon_S-\frac{1}{2}\right)\right\},$$

involves eccentricity, e, and obliquity $\varepsilon_{S,}$ not precession

P. Huybers, 2004.



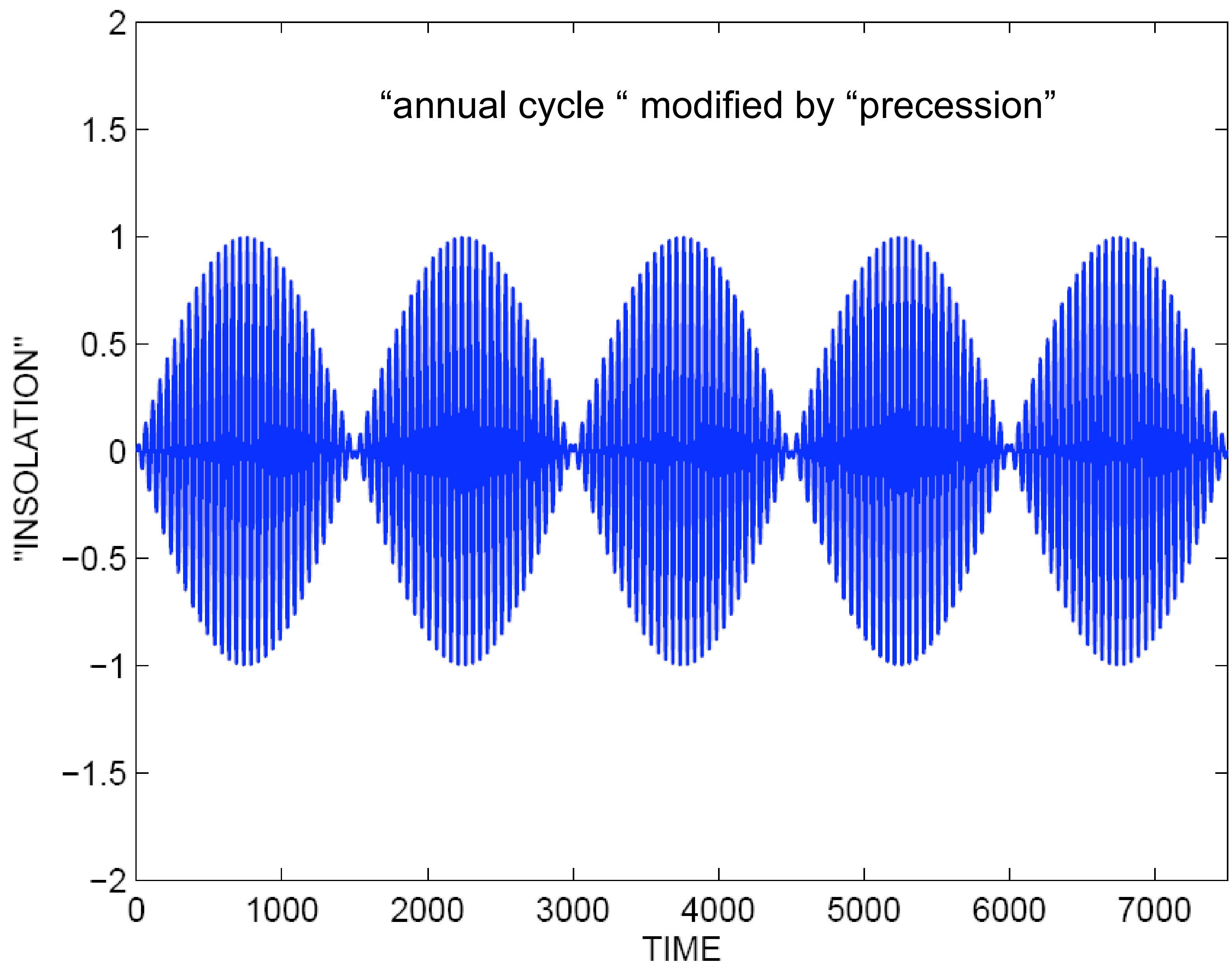
inferred climate spectrum

Spectral Peaks

- Semi-annual
- Annual
- $22KY^{-1}$
- $41KY^{-1}$
- $100KY^{-1}$

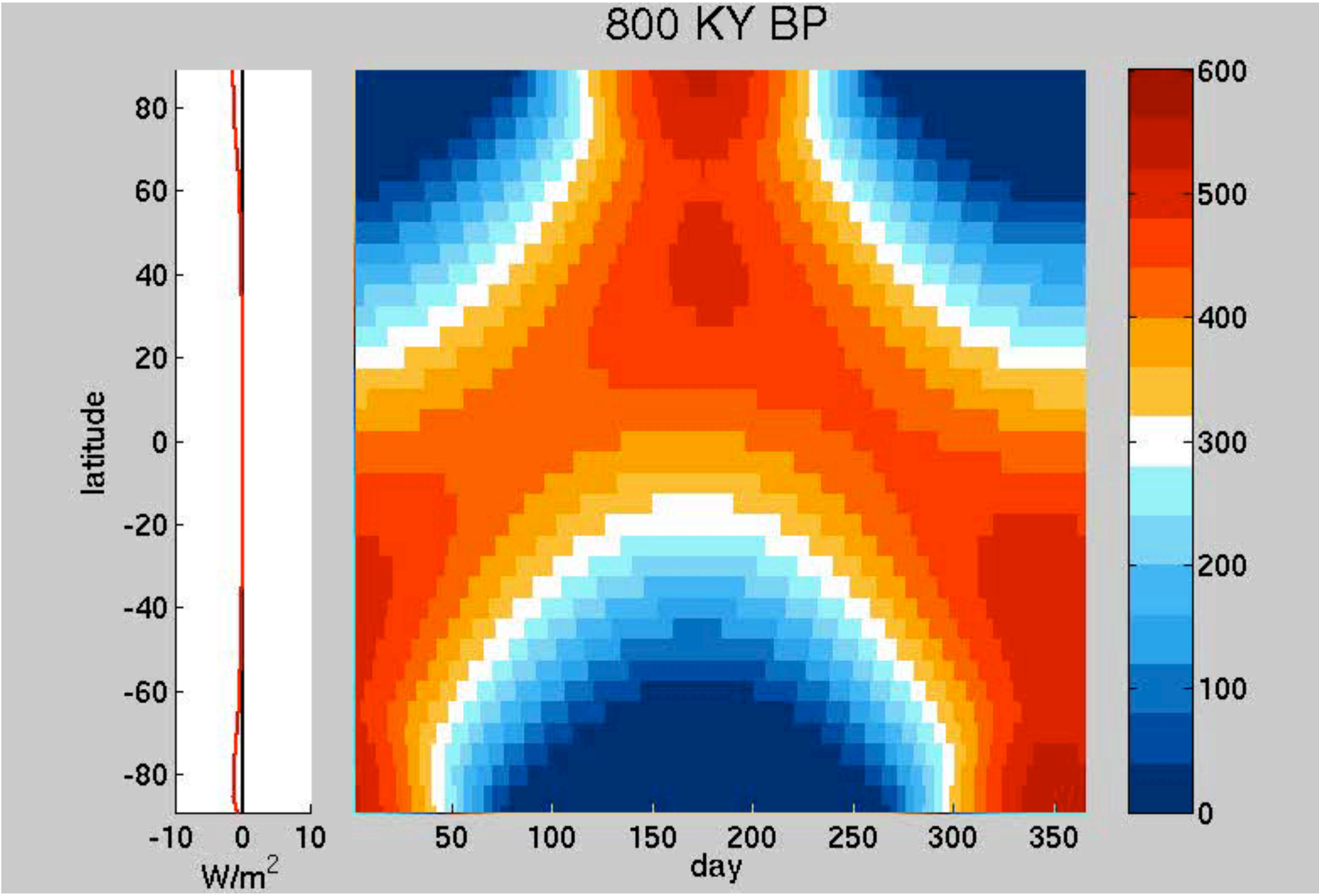
insolation spectrum

Note the broadband character of the low frequency insolation forcing. Not a line spectrum.



“annual cycle “ modified by “precession”
"INSOLATION"
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
0
1000
2000
3000
4000
5000
6000
7000
TIME

Insolation through time and time of year/latitude. P. Huybers, 2004



Eccentricity would give rise to a 100,000 and 400,000 year very weak quasi-periodicity in net insolation, and modulates (splits) the other forcing terms

Obliquity gives rise to a quasi 41,000y periodicity in high latitude insolation symmetric about the equator (a redistribution to/from the polar regions).

Precession gives rise to a quasi-21,000y periodicity in the *amplitude of the annual cycle*, symmetric about the equator. (No energy at 21KY).

The hypothesis of the 100,000 year time-scale glacial cycles as being controlled by eccentricity is a radical and *eccentric* idea. (Compare the invariable-plane idea of Muller and Macdonald.)

How does one get a 100,000 year quasi-periodicity out of ones at 40,000 and 21,000years? Why does the character change at -800,000y?

Crowley and North

Fig. 7.4. Components of precession: (a) axial precession akin to that of a spinning top; (b) precession effect due to changes in elliptical orbit; (c) combined effect of the two results in a slow shift of the equinox through the earth's elliptical orbit. [From Pisias and Imbrie, 1986/87] *Courtesy of Oceanus Magazine (©) 1986 by Woods Hole Oceanographic Institution.*

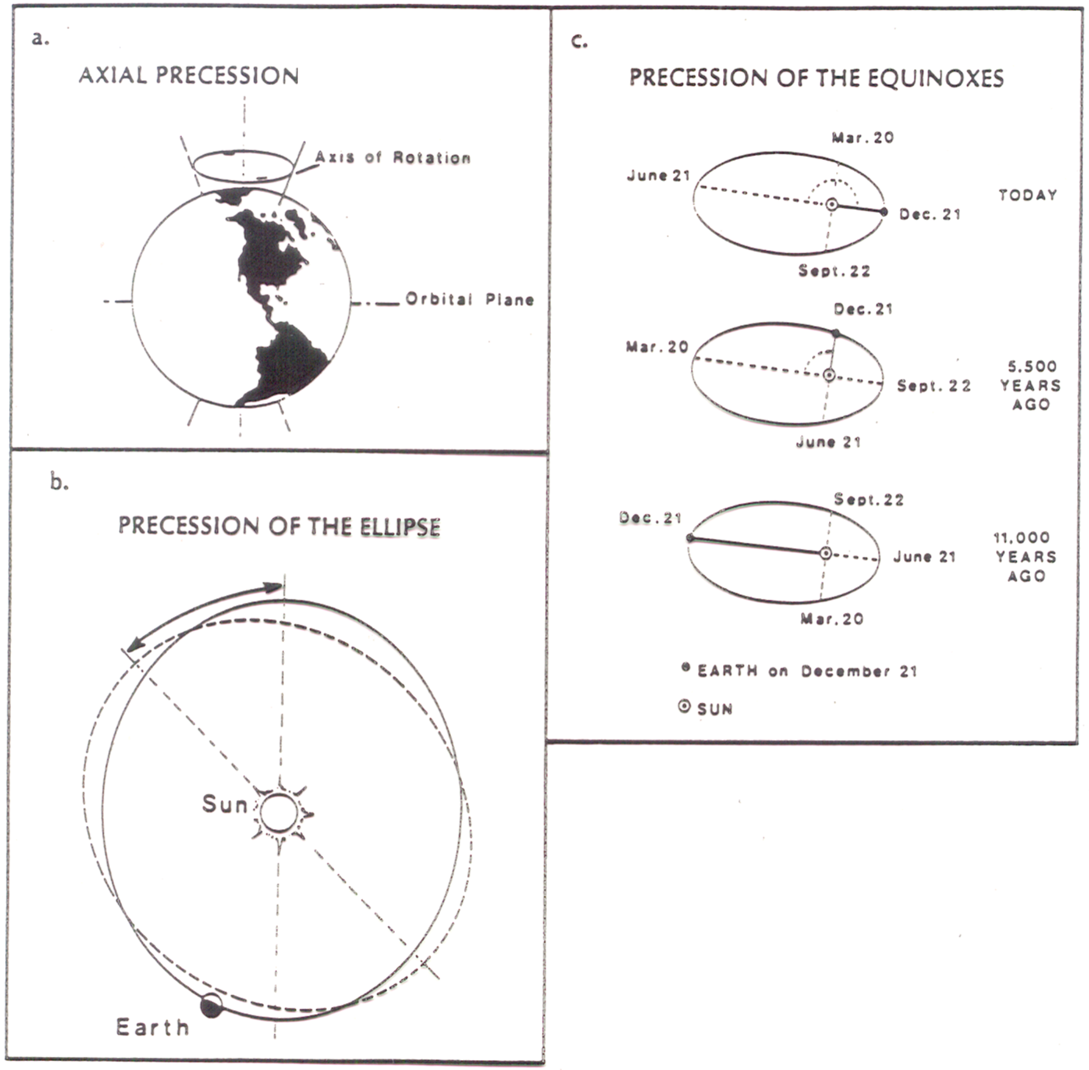
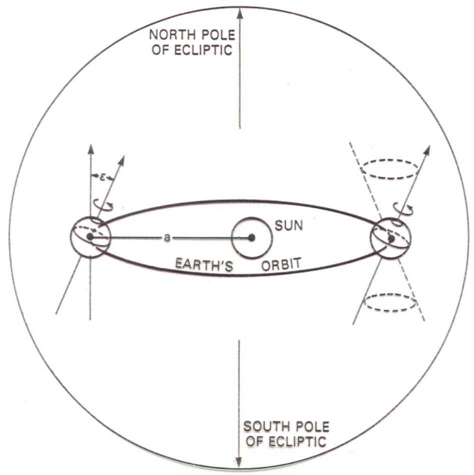
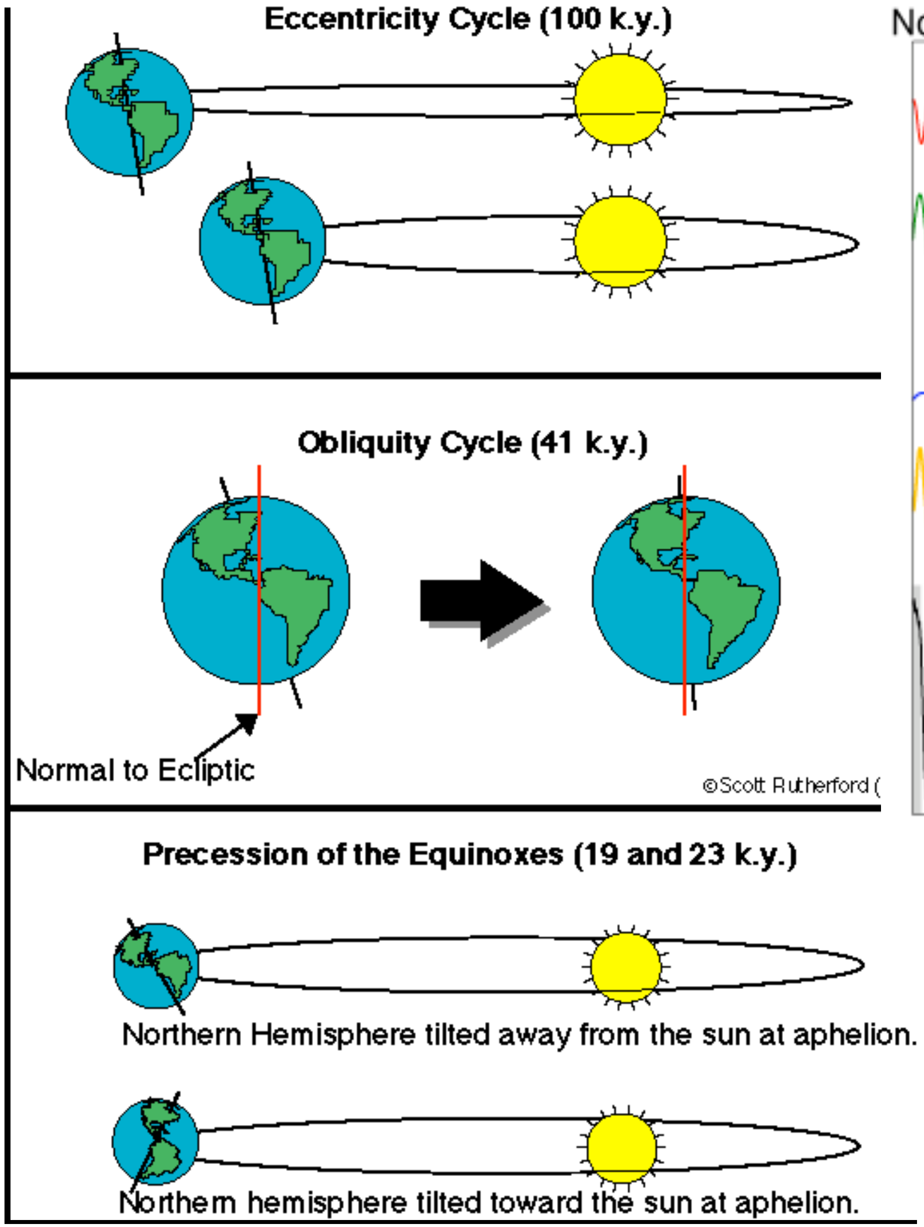
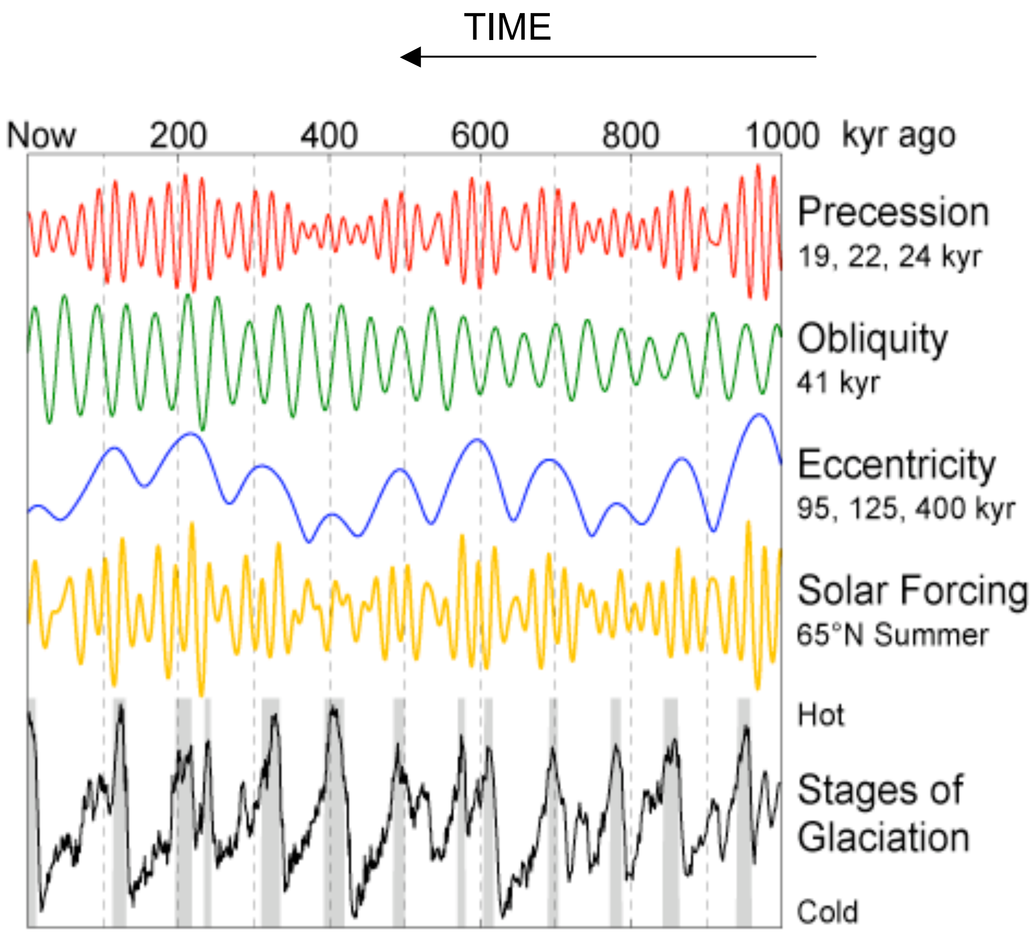


Fig. 7.2. Schematic diagram illustrating effect of planetary forces on the earth's axis and orbit. These forces cause changes in the eccentricity or ellipticity of the orbit **(a)**, the tilt of the rotational pole (ϵ), and the gyroscopic spin of the planet (precession). The precession effect is illustrated more fully in Fig. 7.4. [Modified from Vernekar, 1968]







Note 65N summer insolation, and that precession is the *envelope* of the radiation intensity.

From E. Tziperman

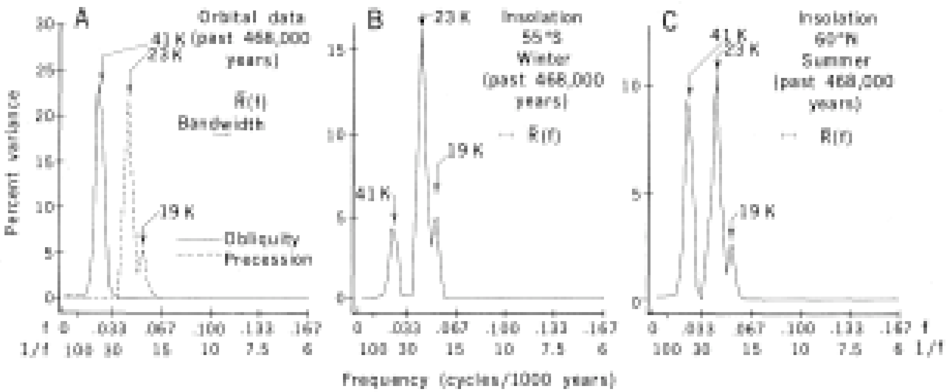


Fig. 4. High-resolution spectra of orbital and insolation variations over the past 468,000 years. Variance (as percentage of total variance per unit frequency band) is plotted as a function of frequency (cycles per thousand years). Arrows indicate weighted mean cycle lengths of spectral peaks (in thousands of years). (A) Spectra for obliquity and precession ($\Delta e \sin \Pi$). (B) Spectrum for winter insolation at 55°S. (C) Spectrum for summer insolation at 60°N. [All data are from Vernekar (39)]

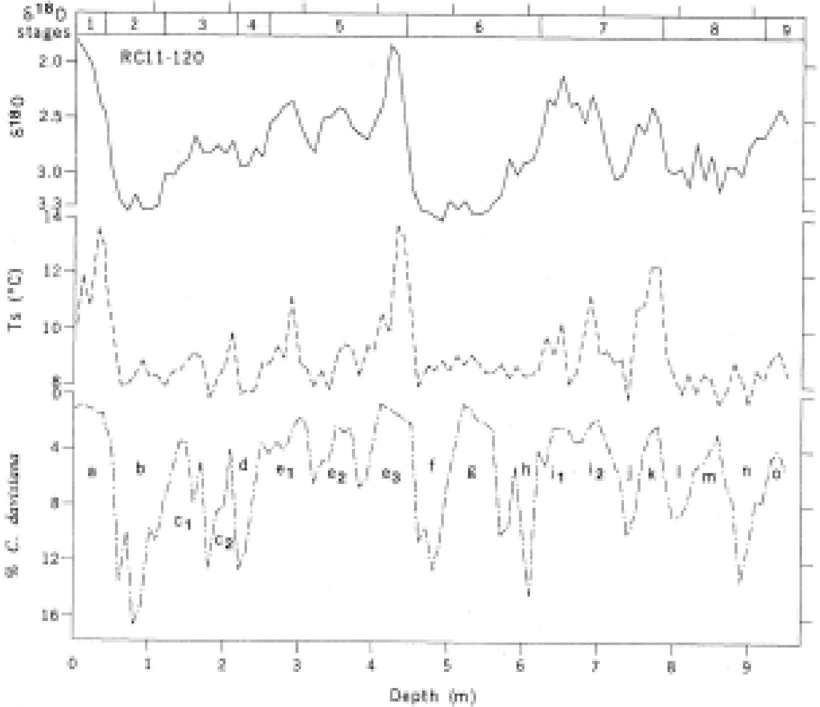


Fig. 2. Depth plots of three parameters measured in core RC11-120: $\delta^{18}O$ (solid line), *Ts* (dashed line), and percentage of *C. davisiana* (dash-dot line). Letter designations of peaks on the latter curve are informal designations of various parts of the record.

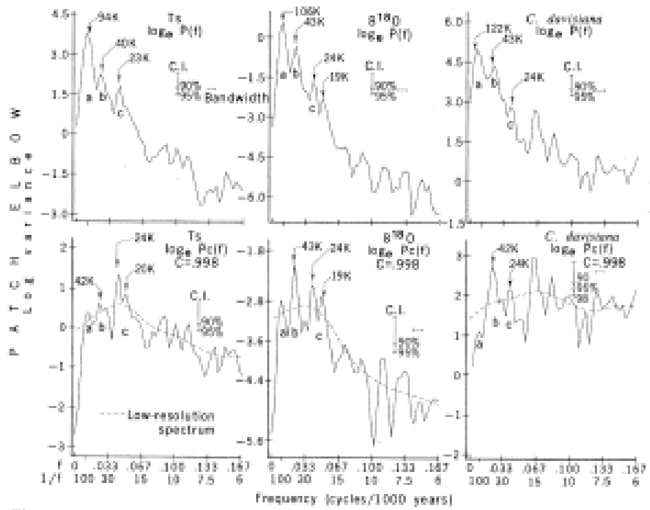


Fig. 6. Spectra of climatic variations (in *Ts*, $\delta^{18}O$, and percentage of *C. davisiana*) in the combined (PATCH) record from two subantarctic deep-sea cores. Calculations are based on the ELBOW age model (Table 2). Arrows without crossbars indicate weighted mean cycle lengths of spectral peaks (in thousands of years). Arrows with crossbars show one-sided confidence intervals (*C.I.*) attached to estimates in the high-resolution spectrum. Prominent spectral peaks are labeled *a*, *b*, and *c*. (Top row) High-resolution spectra from Fig. 5C expressed as the natural log of the variance as a function of frequency (cycles per thousand years). (Bottom row) High-resolution spectra (solid line) and low-resolution spectra (dashed line) after prewhitening with a first-difference filter.

Hays, Imbrie & Shackleton, 1976

Milankovitch Control - The Standard Story

"It is widely accepted that climate variability on time scales of 10^3 to 10^5 years is driven primarily by orbital, or so-called Milankovitch, forcing." (McDermott et al., Science, 2001).

"...it is now quite clear that orbital forcing played a key role in pacing glaciations during the Quaternary...." (Bradley, R. S., Paleoclimatology, Academic Press, 1999, p. 281)

"The orbital theory of climate is the prevailing theory of glacial-interglacial climate change over tens of thousands to hundreds of thousands of years." (Cronin, T. M., Principles of Paleoclimatology, Columbia Un. Press, 1999, p. 131)

"...we confirm that moisture source temperature signal recorded in Vostok deuterium excess over the last 150ka fully reflects the obliquity time-varying relative contribution of low and high latitudes to Vostok precipitation." (F. Vimeux et al., Earth and Plan. Sci. Letts., 203, 2002, p. 829)

"...a strong case has been made that on the time scale of tens of thousands of years, the Earth's climate is being paced by the so-called Milankovitch cycles..." (W. Broecker, Earth Sci. Revs., 51, 137-154, 2000).

"Nevertheless, my null hypothesis is *not* that these time series are white noise or AR(1) processes, but that they contain climatically relevant signals." (Emphasis added. From well-known European climate modeler, private communication, 2002. "Climatically relevant" is a euphemism for "deterministic.")

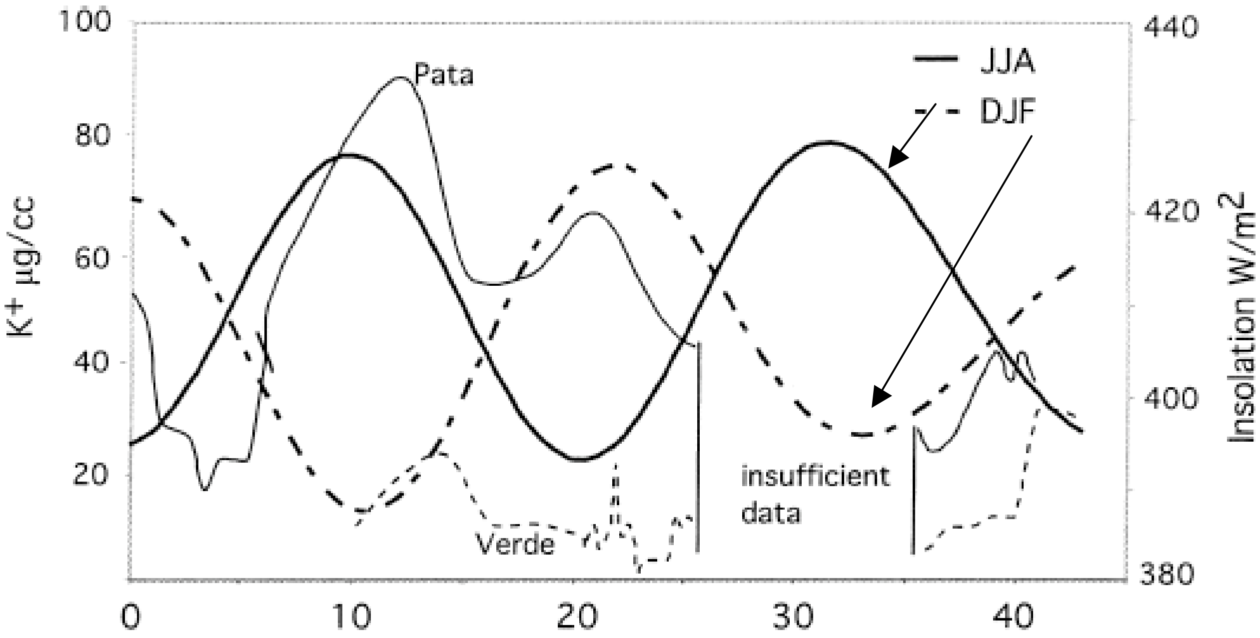


Figure 4. A comparison of June–July–August (JJA) and December–January–February (DJF) insolation at 0° latitude for the last 45,000 years (Laskar 1990; Paillard et al. 1996), with K^+ concentrations in Lakes Verde and Pata. Ages of sedimentary material are based on radiocarbon chronologies calibrated to calendar years BP.

Amazon lakes

Orbital forcing signal in sediments of two Amazonian lakes

M.B. Bush[1,*], M.C. Miller[2], P.E. De Oliveira[3] and P.A. Colinvaux[4]

Journal of Paleolimnology 27: 341–352, 2002.

Possible to discern three types of Milankovitch hypotheses (original hypothesis being that northern hemisphere summer insolation controls climate):

1. Obliquity and precessional band energy is discernible in spectra of climate proxies. Surely true.

2. Obliquity and precessional band energy dominate climate variability between about 18,000Y and 42,000Y periods

3. Obliquity and/or precessional band energy, irrespective of (2) control ("pace"(?)) the 100,000Y variability characteristic of the glacial-interglacial shifts.

What is the evidence?
Note that there have been some dissenting views: Winograd et al., 1992; Roe and Allen, 1999; Steig and Roe, etc. but a distinct minority.

The rectifier problem (Huybers & Wunsch, 2004)

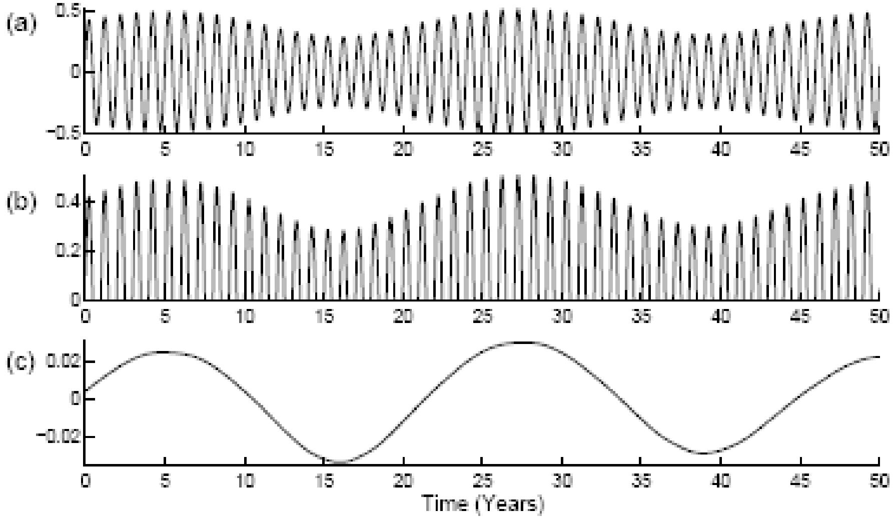


Figure 1. Production of low-frequency variability. (a), Simple amplitude-modulated signal of form (1) having no low frequency content. (b), Rectified signal according to (2) and then, (c), low pass filtered to leave only the envelope function. For visual clarity, the periods of the secular orbital terms are decreased by a factor of 1000 giving roughly 1/23 precession and 1/41 obliquity cycles per annual cycle.

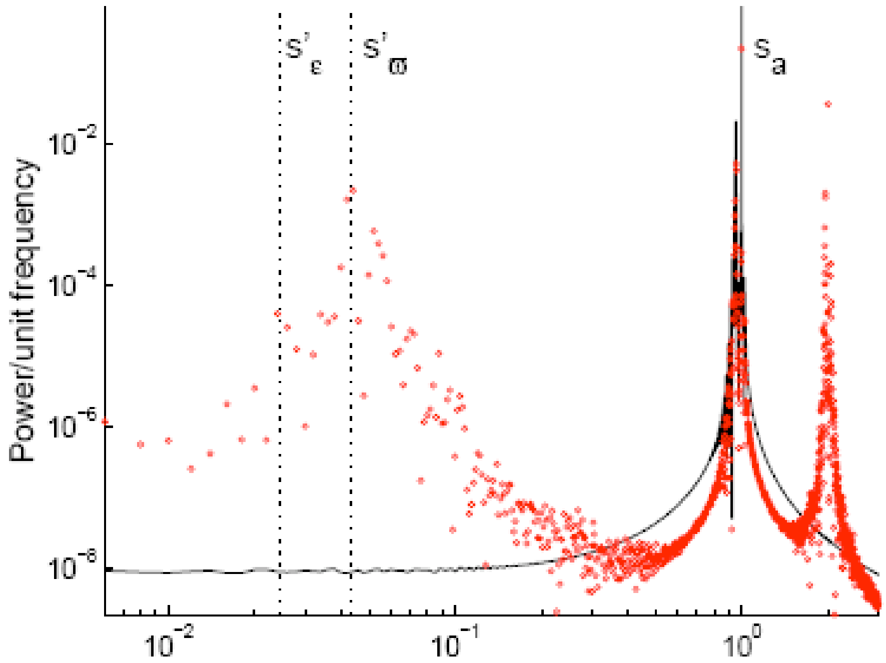


Figure 2. Periodograms of the original and rectified forcings. Solid line is from the original forcing (1) plus a small amount of white noise. The energy near the annual cycle, s_a, is split owing to modulation by the precession and obliquity terms, but there is no excess energy at the lower frequencies. Circles are after applying a half-wave rectifier to the signal. Now excess energy appears at the higher harmonics of s_a as well as the frequencies s'_ϖ and s'_ϵ where the primes indicate that the orbital terms have a 1000 fold decrease in period.

Rectification problem. Precession signals are problematic because any proxy dependent upon seasonality automatically produces apparent 21KY signals – amplitude modulation just as in a radio receiver. Must model the proxy (growing seasons, dust seasons, etc.)

What is the specific evidence for astronomical control?

Consider three null hypotheses. *No* control by:
(1) Eccentricity
(2) Obliquity
(3) Precession

Formal tests (Huybers and Wunsch, Nature, 2004) permit one to reject the hypothesis for obliquity, not for eccentricity or precession.

Given the minuscule fraction of the variance in the insolation bands, how is it possible to control ("pace") the climate system with obliquity?

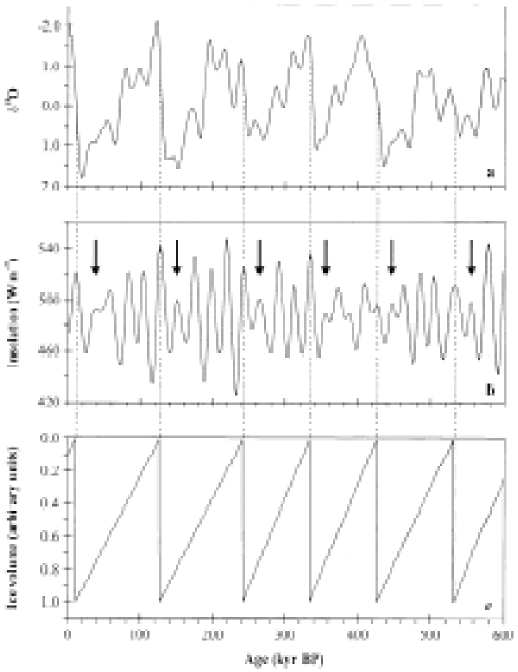
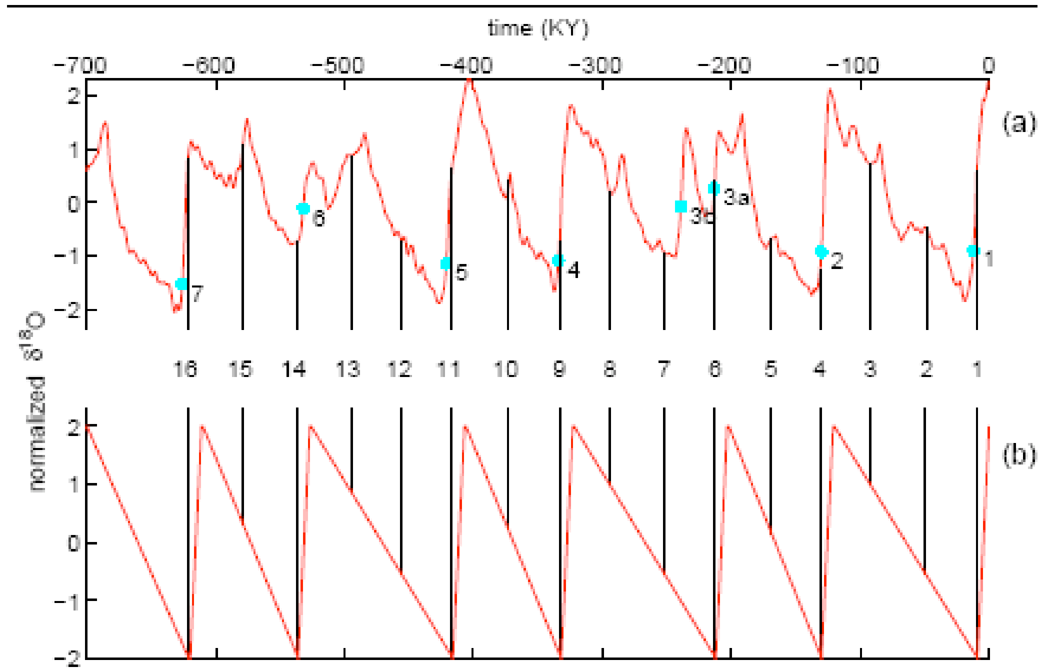
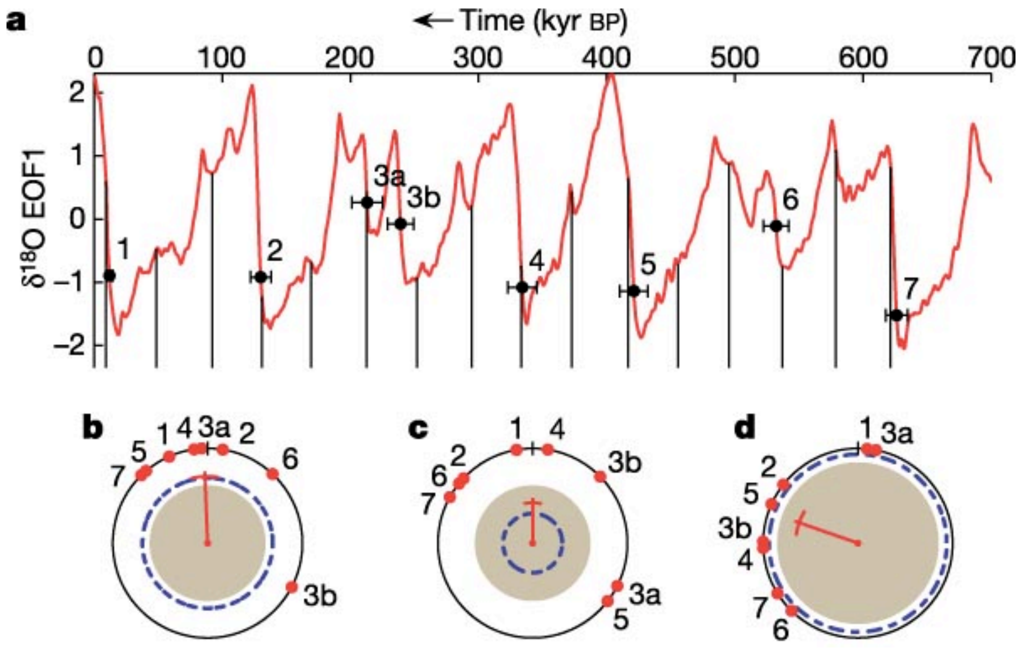


Figure 1. (a) SPECMAP stacked $\delta^{18}O$ composite; (b) insolation for 65°N, June 21, showing the quasi-periodic insolation maxima of unusually low strength (designated by arrows) preceding glacial-interglacial terminations by one precessional cycle in each case; and (c) smooth artificial ice volume signal.

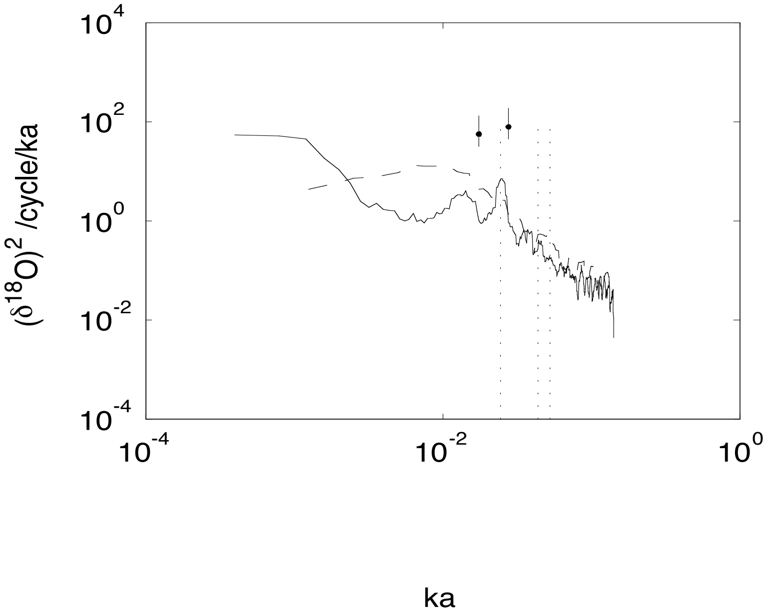


Ridgwell, Watson, Raymo, Paleoceanography, 1999. Claim "100ky variability" is controlled by every 5th or 6th precession cycle. An issue of hemispheric symmetry, and statistically impossible to test: 7 events.

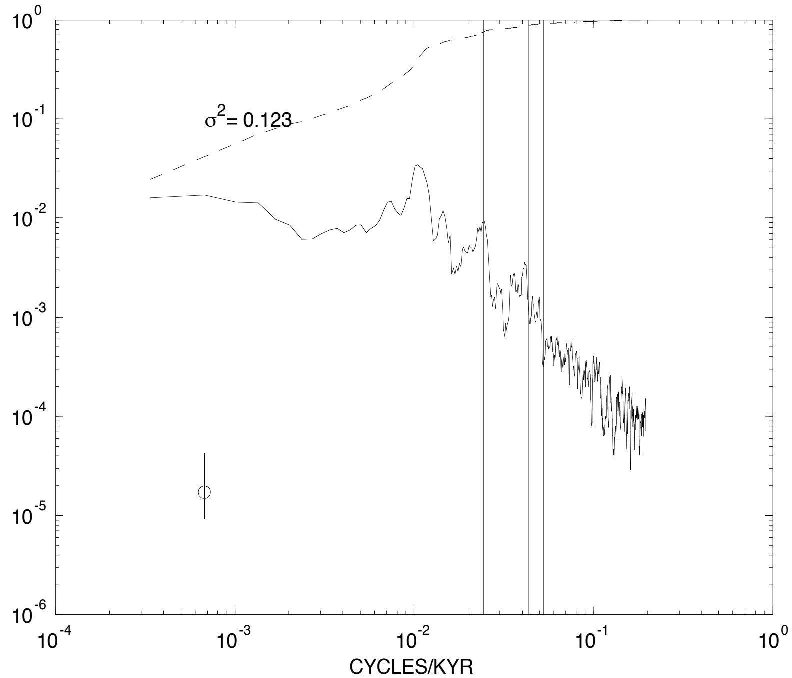


Huybers & Wunsch, 2004

Rayleigh's R test



Power density spectral estimates of the the DSDP607 values of $\delta^{18}O$ before (solid line) and after -800KY. The spectral density of the last 800KY has much more energy at periods around 100KY than one from before that time, but is, at higher frequencies, largely unchanged.



Power density spectral estimate of ODP677 with the Milankovitch frequencies marked by vertical lines (from Wunsch, 2003). Most of the energy in the myriadic band is not associated with the astronomical frequencies.

Very little energy at the astronomical frequencies

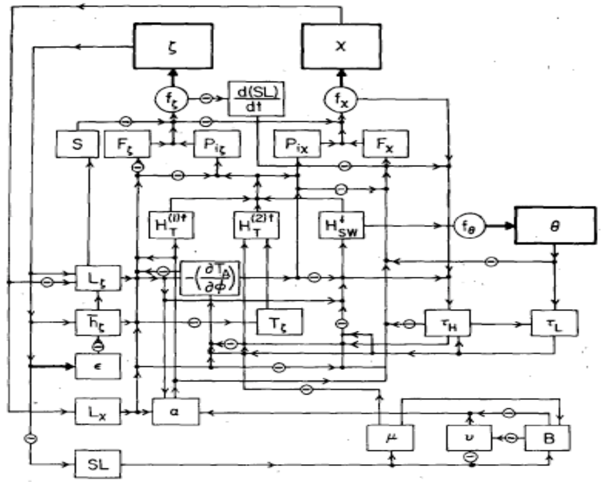
Connection of resonance idea to appearance
of strong lines, and forcing at Milank. frequency. Rahmstorf idea.

Does the climate system have any form of resonance?

Development of Milankovitch and tides.

Four “successful” glacial models: 1

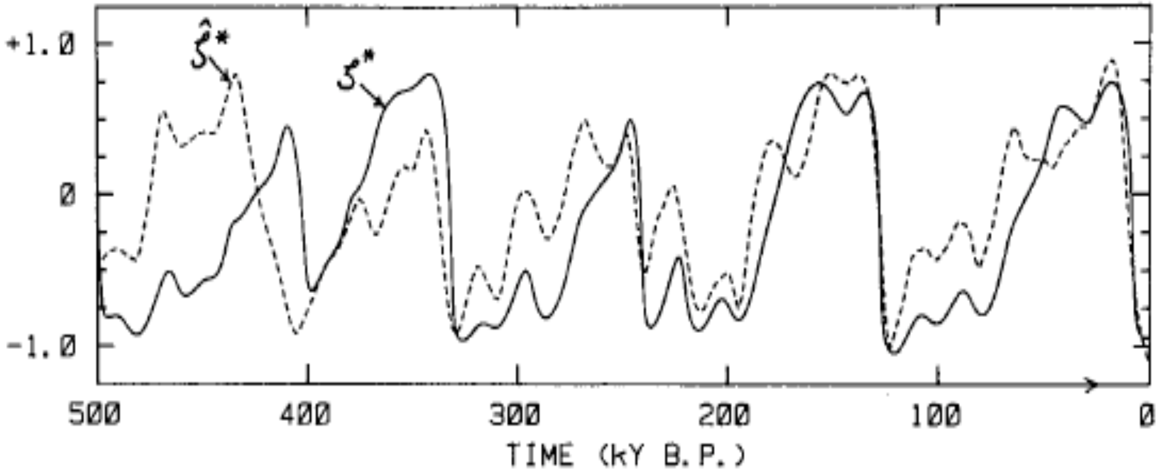
- Saltzman, Hansen and Maasch, 1984: glacial cycles are due to the interaction of land ice, ice shelves and deep ocean temp.

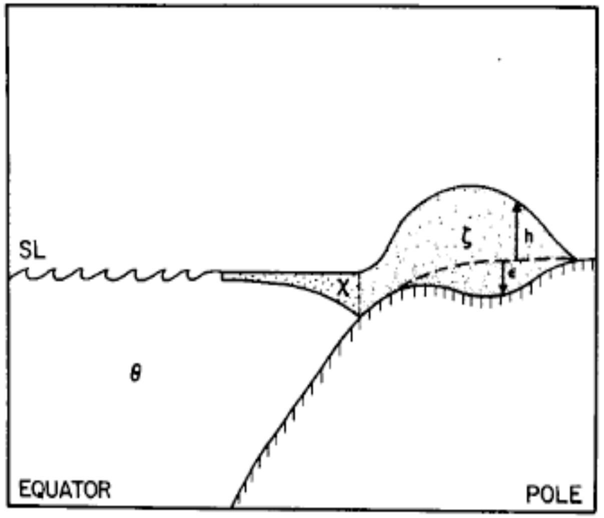


$$\frac{d\zeta'}{dt} = a_0\zeta' + a_1(1 - a_2\chi')\chi' - a_3\theta' + F_\zeta + R_\zeta, \quad (1)$$

$$\frac{d\chi'}{dt} = b_0\zeta' + b_1(1 - b_2\chi' - b_3\chi'^2 - b_4\zeta'^2)\chi' - b_5\theta' + F_\chi + R_\chi, \quad (2)$$

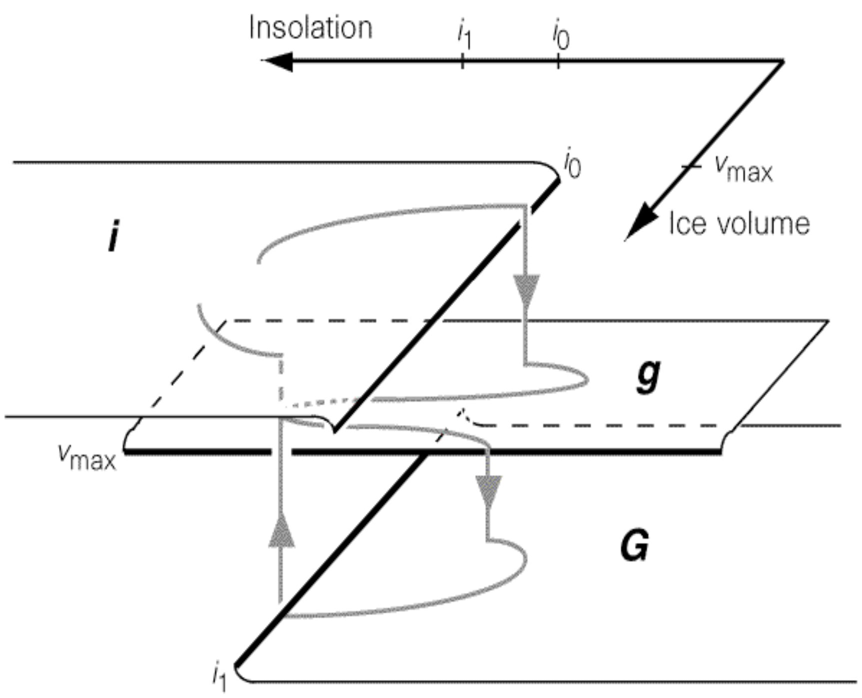
$$\frac{d\theta'}{dt} = c_0\zeta' + c_1\chi' - c_2\theta' + F_\theta + R_\theta, \quad (3)$$

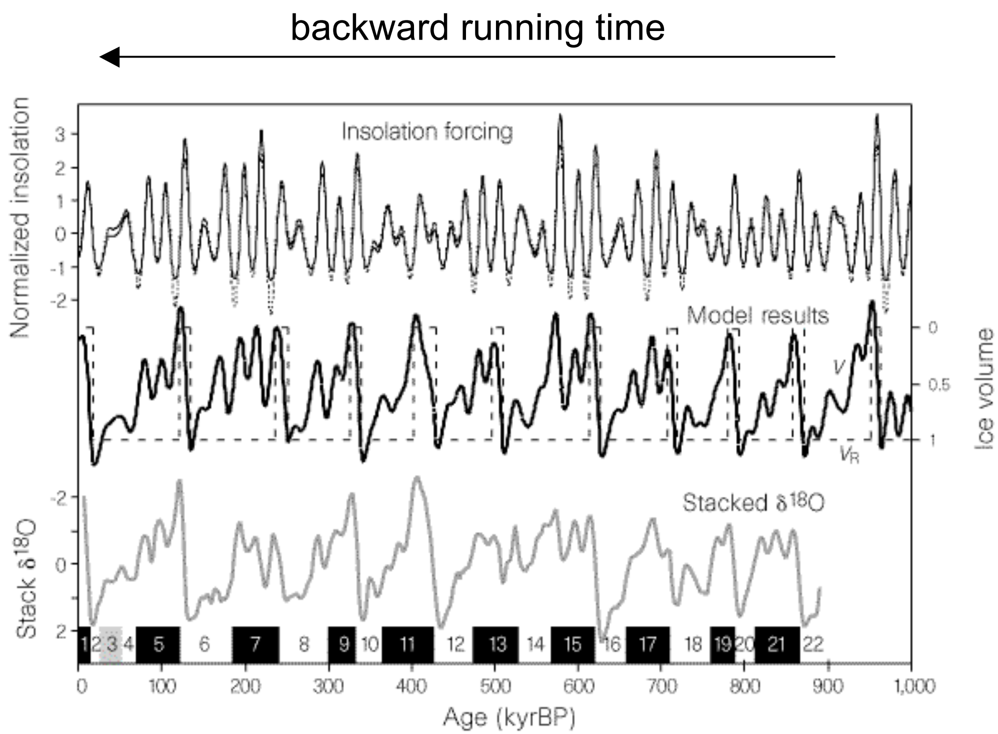




Four “successful” glacial models: 2

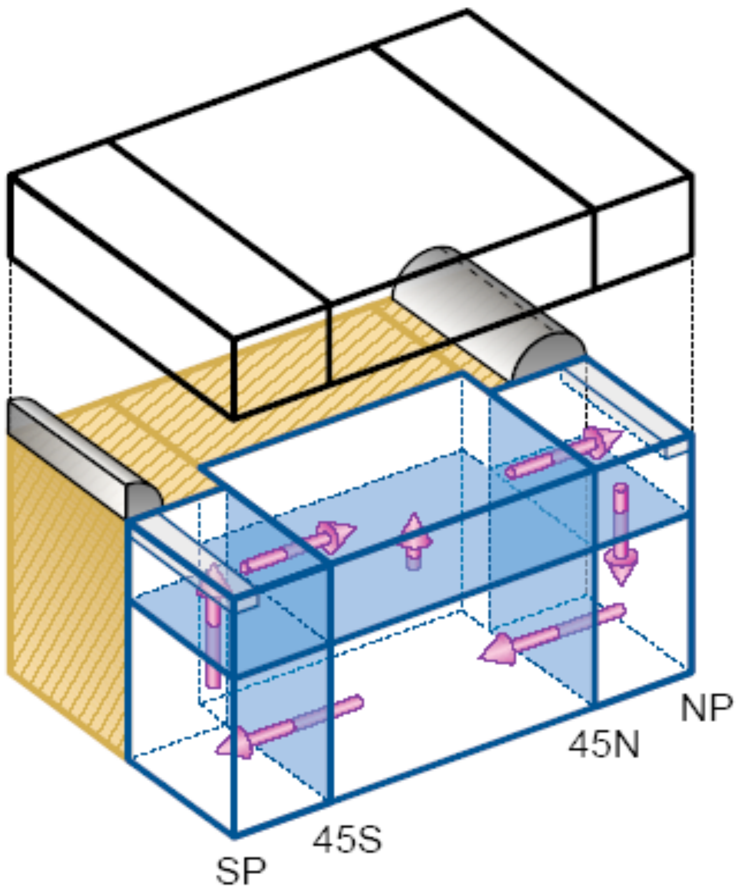
- Paillard 1998: 3 steady states, one equation, transition between steady states based on Milankovitch forcing.
- Glacial cycles are due to jumps between steady states of ocean circulation forced by insolation

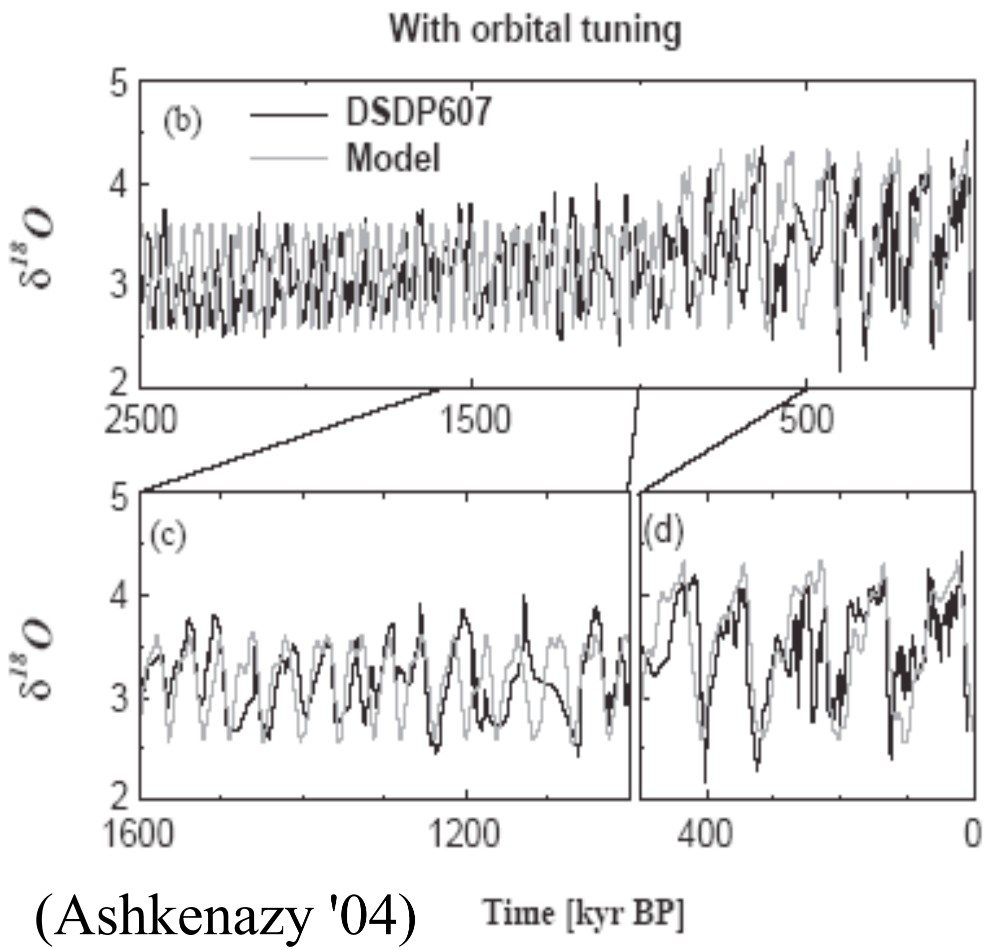




Four “successful” glacial models: 3

- Gildor and Tziperman 2000: “sea ice switch”: land ice grows during warm periods (small sea ice cover) and retreats during cold periods (large sea ice cover);





(Ashkenazy '04)

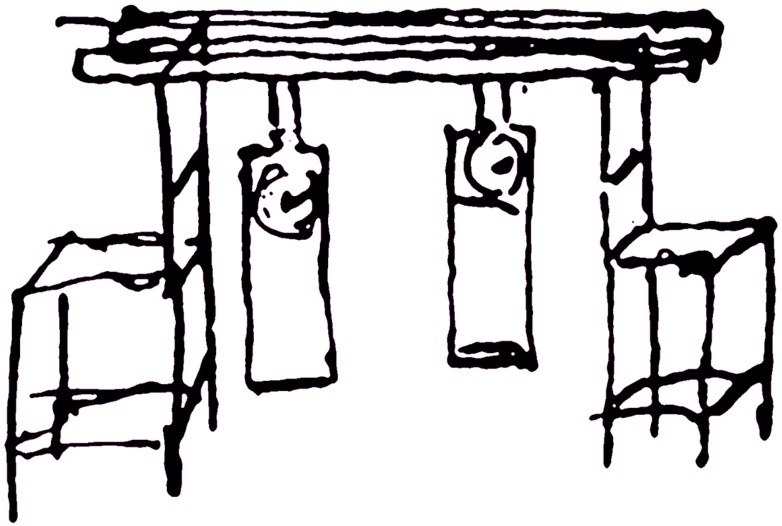
There are 8 glacial cycles in the last million years. Some of the models have as many as 20 parameters. What is one to do?

Almost any nonlinear model produces entrainment of the carrier.

A variety of nonlinear models all works: see Tziperman, Huybers, Raymo, Wunsch, 2006, Paleoceanog.

Why is it so `simple' to fit the glacial cycles?

The question (Saltzman, Hansen & Maasch 1984): *"How does small amplitude periodic forcing control phase in a complex nonlinear oscillatory system, and is there a good physical interpretation for this phase locking phenomenon?"*



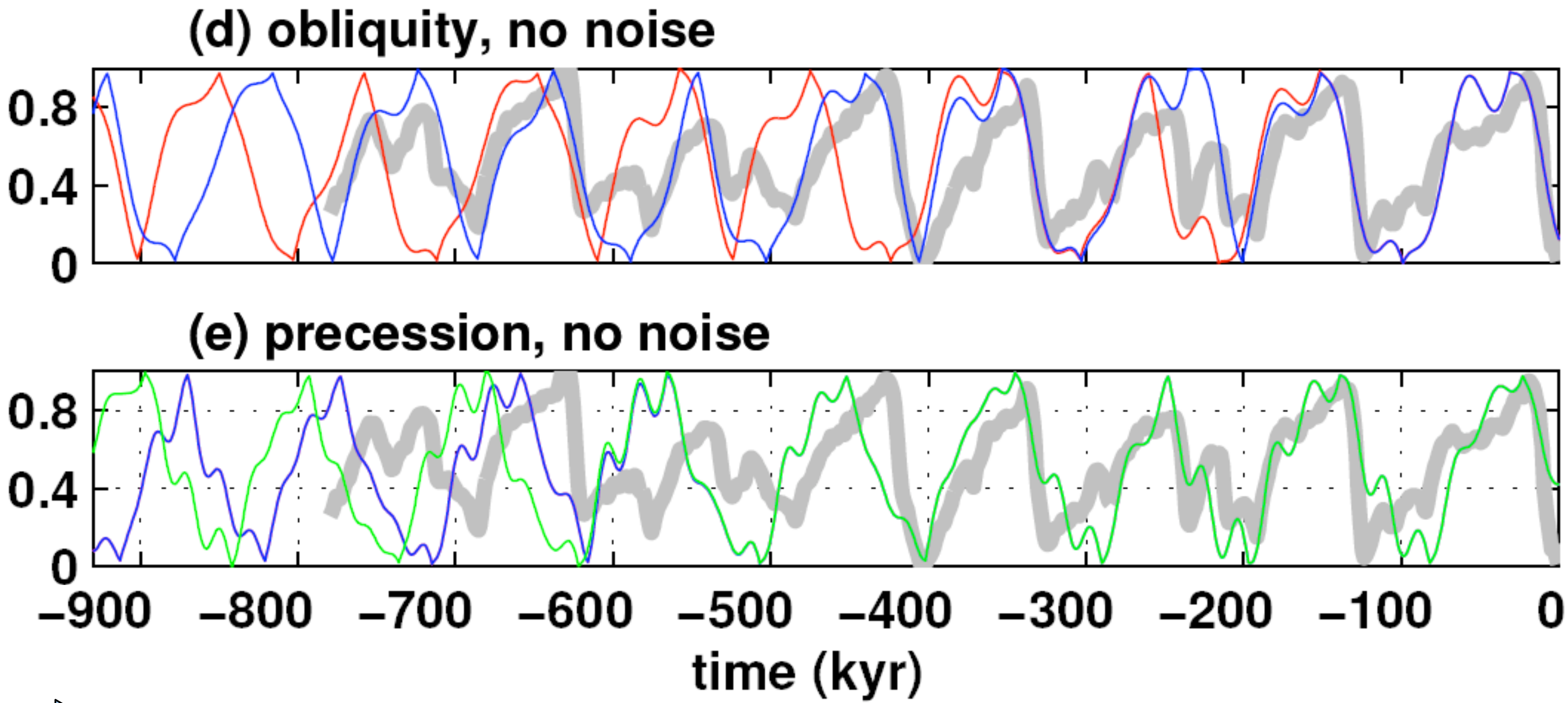
The answer: It's "nonlinear phase locking":

1665, Christiaan Huygens, Dutch mathematician, astronomer and physicist. While working on design of precise pendulum clocks, suitable for determination of a ship coordinates in the sea, he observed and described synchronization of two clocks placed on a common support.

http://www.agnld.uni-potsdam.de/~mros/synchro.html

Which orbital parameter is responsible for the phase locking? Obliquity? Precession? Both?

Model time series under obliquity forcing and under precession forcing:



Possible to obtain a reasonable fit to ice volume record with precession, obliquity, or 65N insolation forcing. Model too simple to determine which is more important. Huybers and Wunsch (2005): found correlation with obliquity, inconclusive regarding precession.

"Quantization" of glacial period by obliquity/ precession: Nonlinear resonance/ phase locking:

$$\omega/\omega_f = p/q$$

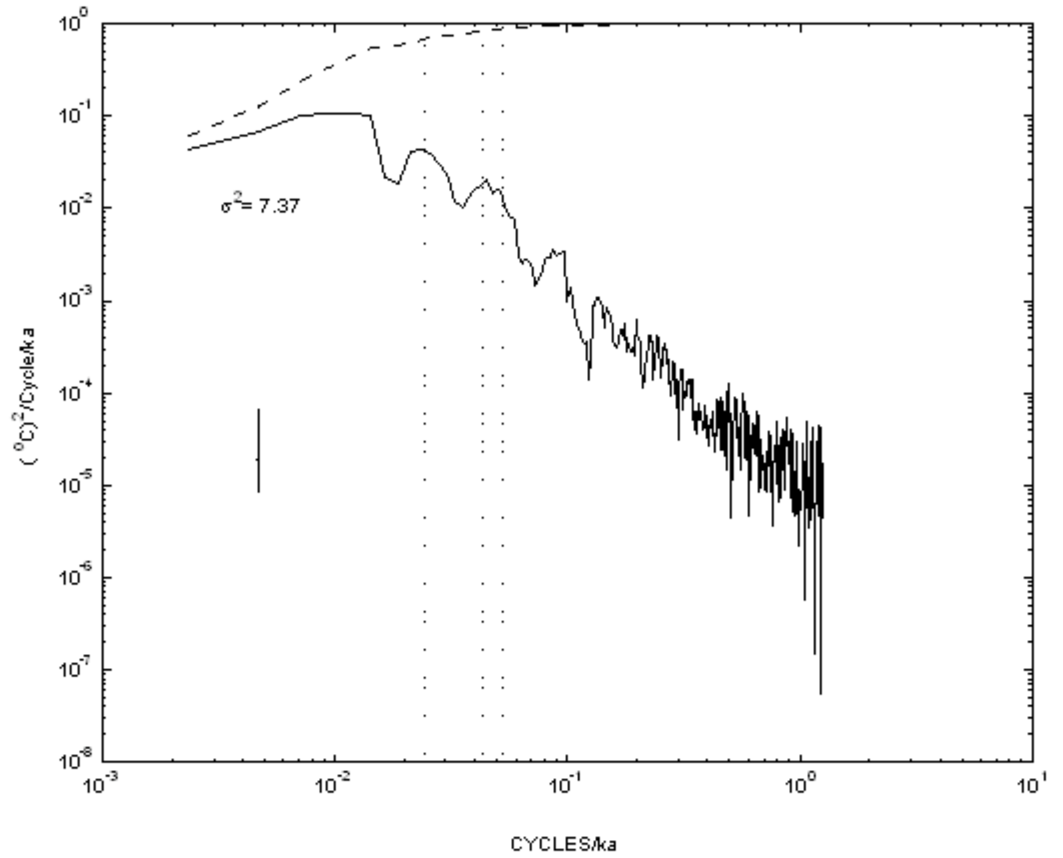
- Linear resonance: forcing frequency = natural oscillator frequency

$$\omega/\omega_f = 1/1$$

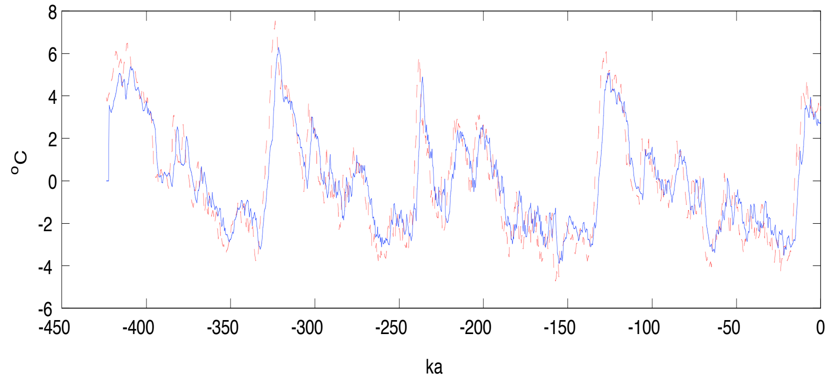
$$\omega/\omega_f = p/q$$

- Nonlinear resonance: any Integer ratio
- Glacial periods: 80 kyr = obliquity X 2; *p/q* = 2/1
  100 kyr = obliquity X 5/2; *p/q* = 5/2
  120 kyr = obliquity X 3; *p/q* = 3/1
  80 kyr = precession X 4; *p/q* = 4/1
  100 kyr = precession X 5; *p/q* = 5/1
  120 kyr = precession X 6; *p/q* = 6/1

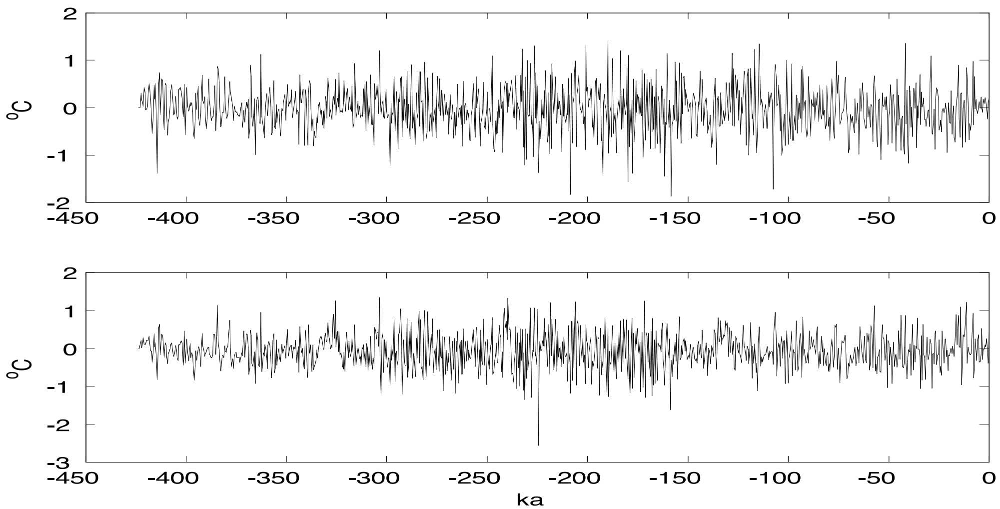
- Fourth model ---Stochastic

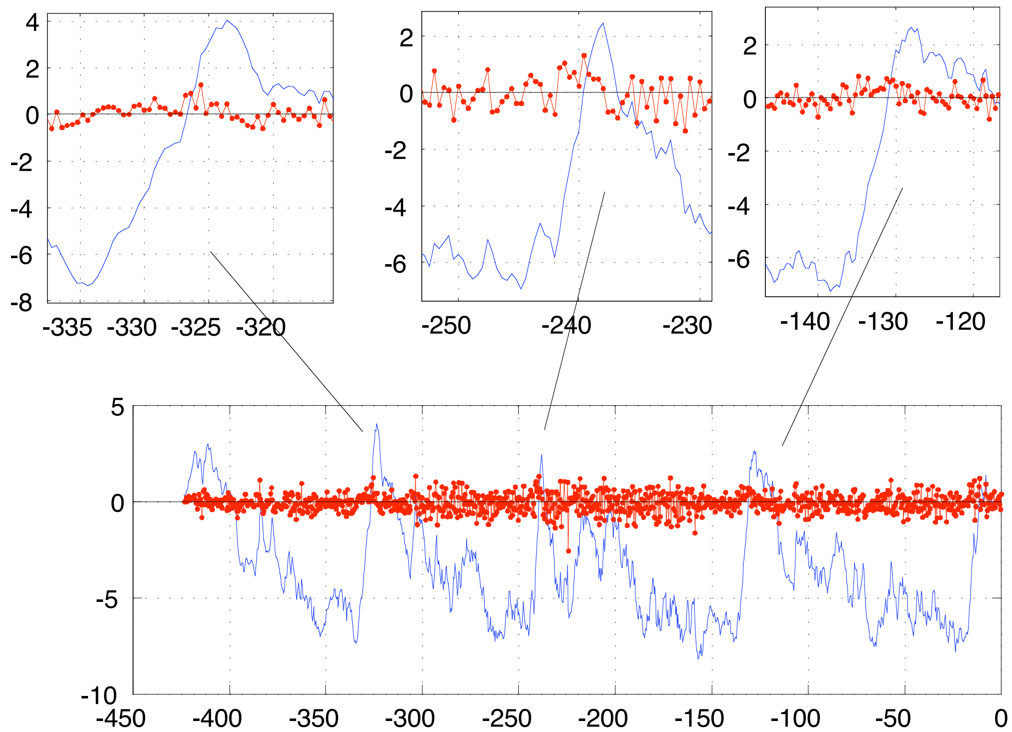


Vostok core power density estimate. Obliquity and precession frequencies marked. Main characteristic is a red noise behavior.



A simple autoregressive fit --- AR(2)--- succeeds in describing the time series: x(t) =ax(t-1)+bx(t-2)+white noise. Except right at the deglaciations.





A random walk plus a weak obliquity forcing.

Huybers and Tziperman, 2007, submitted, made an ice/atmosphere model to explore further the reasons why obliquity seems to dominate:

A zonally averaged energy balance model (as in Pollard, 1978) coupled to an ice sheet which deforms by Glen’s Law and ablates by a simple assumption about insolation above a threshold.

HUYBERS AND TZIPERMAN: 40KY GLACIAL CYCLES X - 81

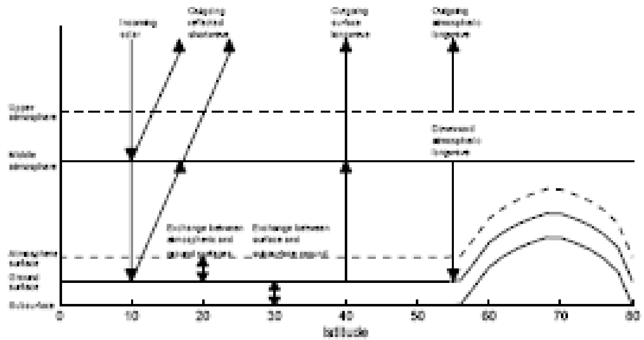


Figure 9. Schematic of the energy fluxes. Levels from top to bottom are the upper and middle atmosphere, atmospheric surface layer, ground/ice surface, and subsurface. Arrows indicate locations at which radiative, diffusive, or turbulent heat fluxes are absorbed or reflected. Note that the atmosphere radiates upward only at the upper atmospheric level. The model has one degree resolution in latitude. Surface and subsurface boxes are represented as either ground or ice and, in this case, an icesheet extends equatorward to 55°. For the sake of visual clarity, the y-axis is not drawn to scale.

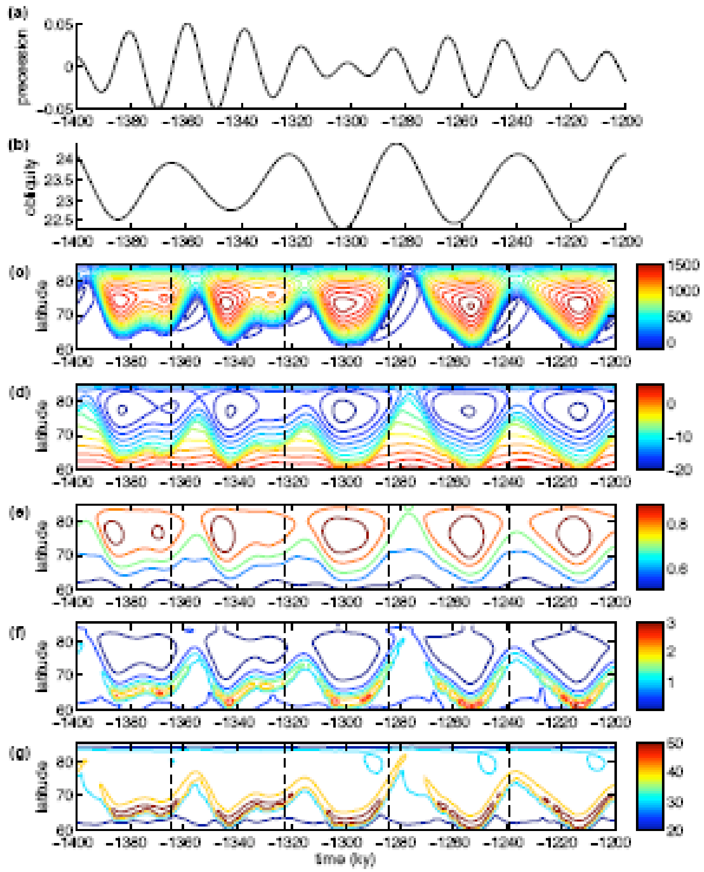


Figure 4. Time evolution of annual average model quantities. For reference the climatic precession parameter (a) and Earth's obliquity (b) are shown. (c) The height of the surface is contoured in 200 meter intervals. Negative values occur where ice has retreated from an isostatically depressed bed. Also shown are the annual average temperature (d, °C), accumulation (e, meters per year), ablation (f, meters per year), and total heat flux into the surface including short-wave, long-wave and sensible heating (g, W/m^2). Vertical lines indicate maxima in obliquity.

height

ablation

dashed lines are max. obliquity

Other oddities of determinism

Does the climate system support linear (or non-linear) resonances?

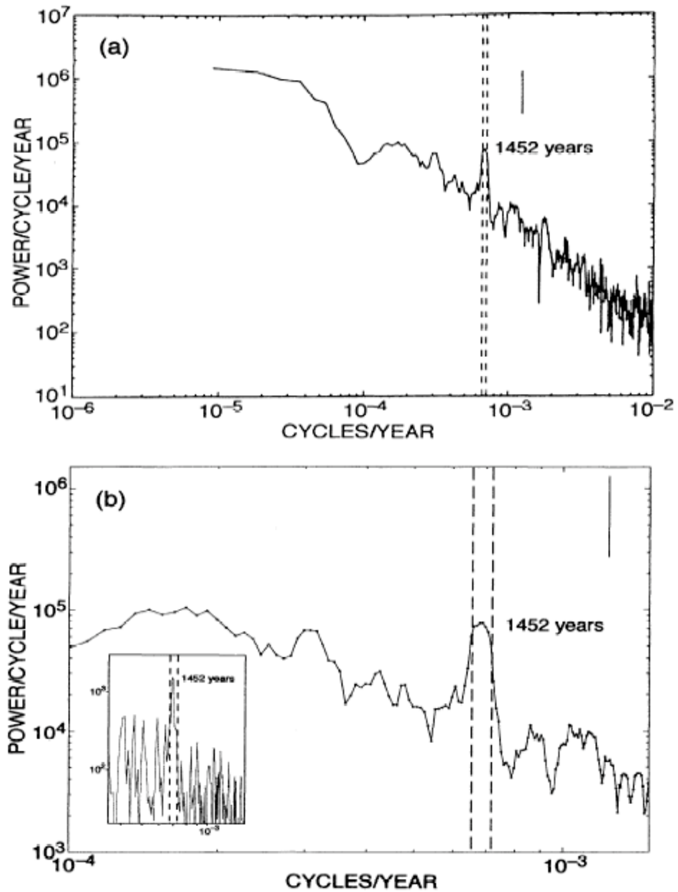


Figure 1. (a) A multitaper spectral estimate of the Polar Circulation Index (PCI) of *Mayewski et al.* [1997]. An approximate mean 95% confidence limit is shown. The peak is a maximum at ~1452 years. The power scale is logarithmic, permitting the use of a near-constant confidence interval shown as a vertical line segment. The vertical dashed lines show the predicted alias position of the anomalistic year at 1/1508 cycles per year and the position of the tropical year at 1/1407 cycles per year. (b)The same as in Figure 1a, except on an expanded scale. The inset is the periodogram (simply the square of the Fourier series coefficients) showing that the peak has a bandwidth of no more than two cycles in 110,000 years. Vertical dashed lines are the same as in Figure 1a.

Why is there a spectral peak in the GISP ice core at exactly 1452y? Oceanic resonance? Solar oscillation? Tidal interaction?

Simplest explanation (not accepted by the paleocommunity): core is sampled at integer multiples (50) of the civil year (365 days). Alias periods of the tropical and anomalistic years occur at exactly 1470y. (The stroboscope effect.)

$$1/(50x365)-m/365.25=1/(1470x365)$$

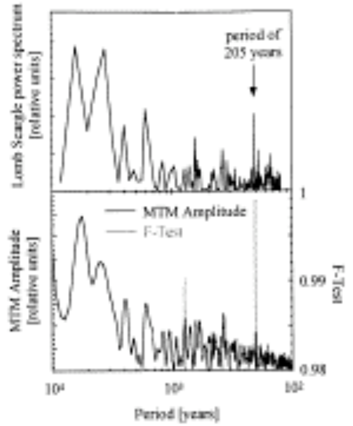


Figure 2. a) Lomb Scargle [*Scargle*, 1982; *Haubold and Beer*, 1992] power spectrum of the ^{10}Be flux in the time interval 25 to 50 kyr BP. b) Multitaper Method (MTM) harmonic analysis of the ^{10}Be flux. The parameter values are $N\Omega = 8$ (bandwidth), $K = 10$ (tapers). The left axis is the estimated MTM Amplitude (solid line) and the right axis is the statistical F-test (dotted line).

Wagner et al., GRL, 2001

Claim of pure frequencies in the sun – driving pure frequencies in climate

Rahmstorf argues that so-called Dansgaard-Oeschger events occur at integer multiples (2,3,…,7) of the 1470 year period.

17 - 2 RAHMSTORF: TIMING OF ABRUPT CLIMATE CHANGE

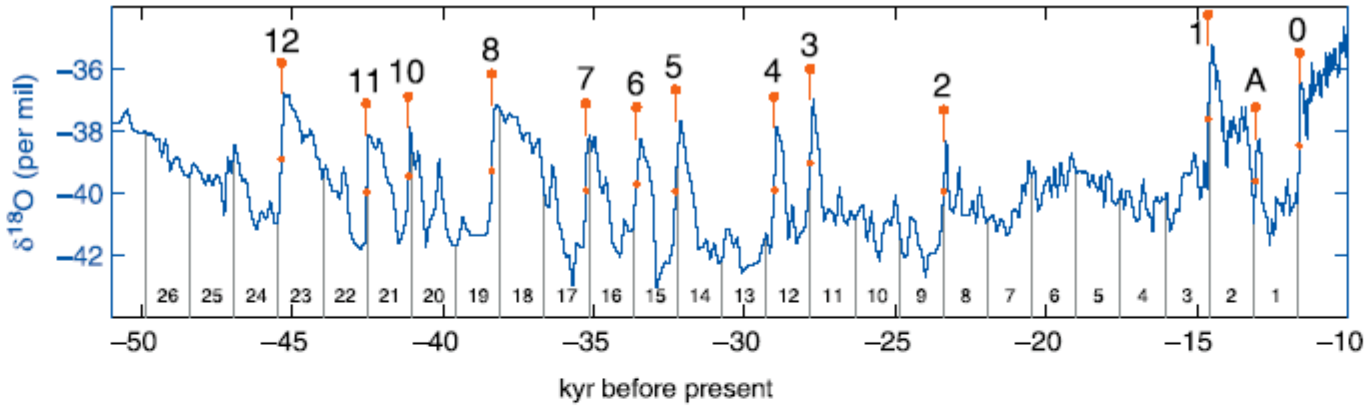


Figure 1. The GISP2 climate record for the second half of the glacial. Dansgaard-Oeschger warming events found by the objective detection algorithm are labeled with red flags. The grey vertical lines show 1,470-year spacing, small numbers at the bottom count the number of 1,470-year periods from DO event 0.

What sort o mechanism could create such a phenomenon?

Magic of 65N June insolation controlling climate. How is this possible?

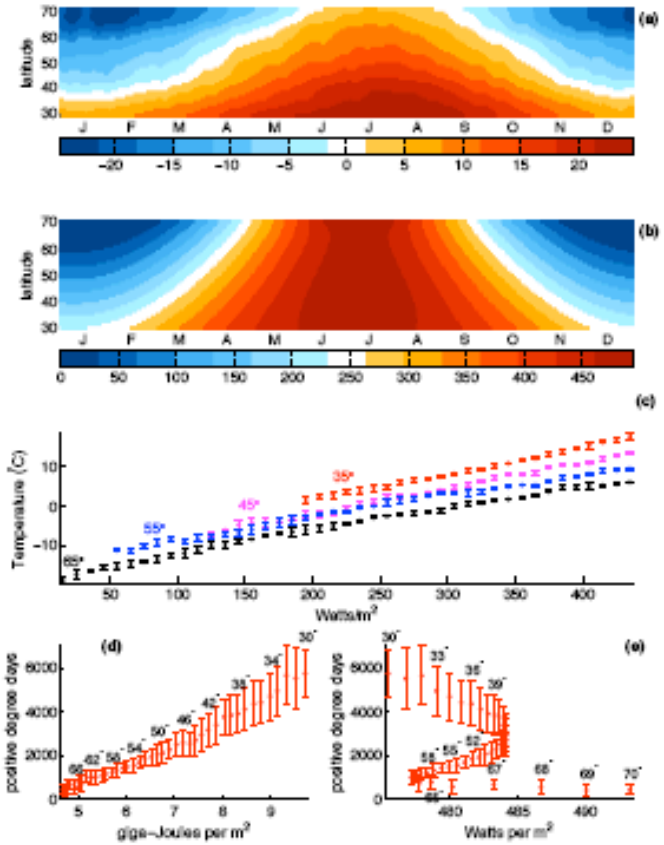


Fig. 1: Relationships between insolation and temperatures. (a) Temperature in °C contoured as a function of latitude and month. Temperatures, $\bar{T}$, are diurnal averages from WMO stations and are averaged according to latitude after adjusting for elevation using a lapse rate of 6.5°C/Km. (b) Insolation at the top of the atmosphere. (c) $\bar{T}$ plotted against insolation for different latitudes ($r^2 > 0.99$). Latitude bins are 10° and insolation bins are 10W/m^2 where insolation has been lagged by one month. (d) Positive degree days plotted against summer energy (r^2=0.98). (e) Positive degree days plotted against the intensity of diurnally averaged insolation on June 21st (r^2=0.1).

P. Huybers, 2006

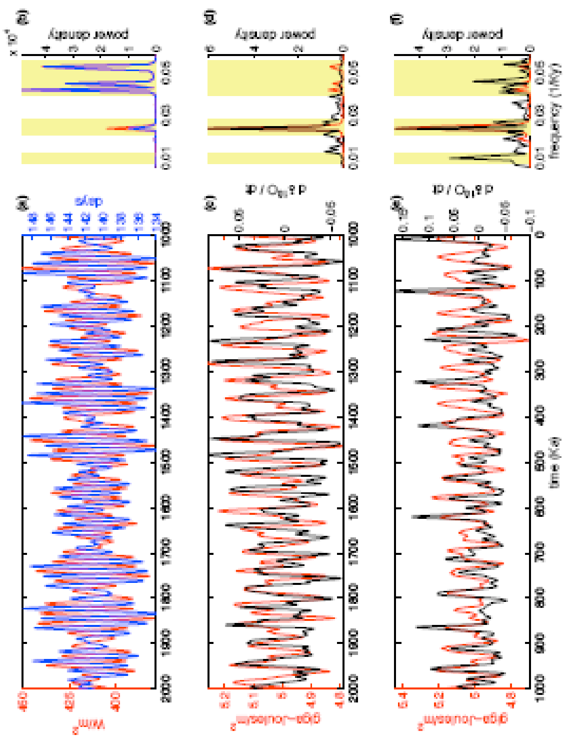


Fig. 2: Insolation forcing and Pleistocene glacial variability. (a) Number of days insolation is above 275 W/m^2 (blue) and the average insolation intensity during this interval (red). Intensity and duration are anti-correlated. (b) Spectral estimate of the duration (blue) and intensity (red) showing that the majority of the variability is at the precession periods. Shaded bands from left to right indicate the 100Ky, 41Ky (obliquity), and 21Ky (precession) bands. (c) Summer energy (red) and the time rate of change of $\delta^{18}O$ (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 41Ky obliquity period. (e,f) Same as c and d but for the late Pleistocene. Note that the time rate of change of $\delta^{18}O$ has variability at the 100Ky period not present in the forcing.

12

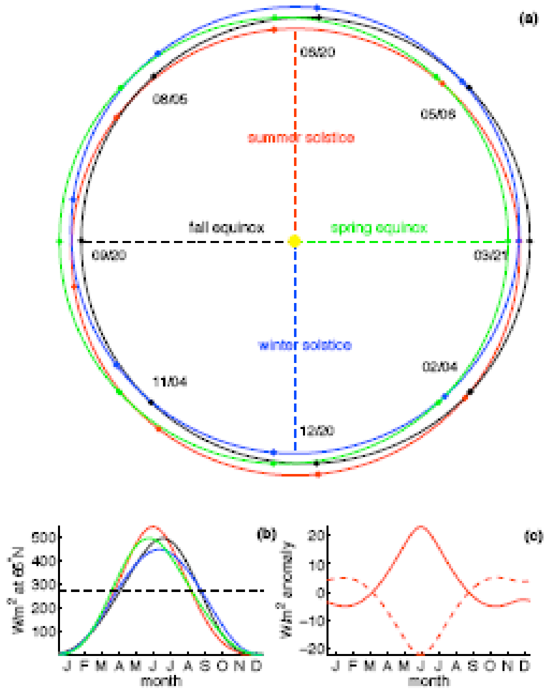


Fig. 3: The Earth's variable orbit around the sun. (a) Earth's orbit when perihelion occurs at Northern Hemisphere summer solstice (red), fall equinox (black), winter solstice (blue), and spring equinox (green) corresponding to the orbital configuration near 220.2, 214.6, 209.2, and 203.5 Ky ago respectively. The eccentricity of Earth's orbit averages 0.05 during this interval. The orbit is to scale and oriented so that vernal equinox always occurs at the three o'clock position. March 21st is referenced to the vernal equinox, and the location of the Earth is shown every 45.7 days (colored dots and dates given as month/day). Earth moves counter-clockwise. Note that the orbit having perihelion during Northern Hemisphere summer (red) reaches fall equinox the soonest. (b) Seasonal variations in insolation at 65°N. The x-axis is labelled with the mid-point of each month. The orbit with perihelion at summer solstice (red) achieves the greatest insolation intensity but also has the shortest duration above a 275W/m^2 threshold (indicated by the horizontal dashed line). (c) Anomalies in insolation for obliquity values of 22.1° (dashed) and 24.5° (solid) relative to a mean obliquity of 23.3° for the orbit with perihelion at summer solstice.

Strongly suggests that insolation control depends upon the hemispherically integrated insolation above the ablation temperature of ice.

P. Huybers, 2006

Inferences/Conclusions:

There are no internal pure resonances in the climate system. (Although a favorite among much of the paleoclimate community, would be an amazing phenomenon in a turbulent fluid.)

There is evidence that obliquity controls the timing of glacial cycles during the last 800,000 years. Obliquity dominates prior to that time.

There is no direct evidence for precessional control of climate, and supposed signals *may* be nothing but rectification of the seasonal cycle by the proxies
Conceivably the signal is suppressed in deep-sea records, but there are other reasons why it can be artificially present.

With only eight nominal 100KY glacial cycles, distinguishing among the infinite number of possible models is likely impossible if restrict attention to the poles or a limited number of age-model uncertain deep-sea cores.

System is likely combined stochastic and deterministic, somewhat like weather and the seasonal cycle.

Thank you.