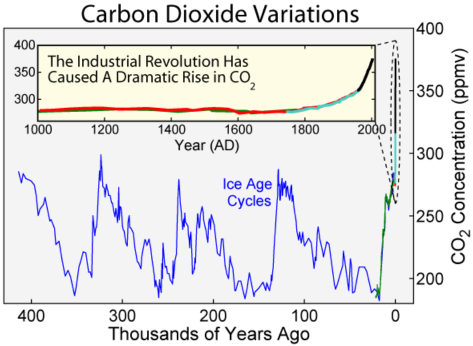
MILANKOVITCH CYCLES AND THE EARTH'S CLIMATE

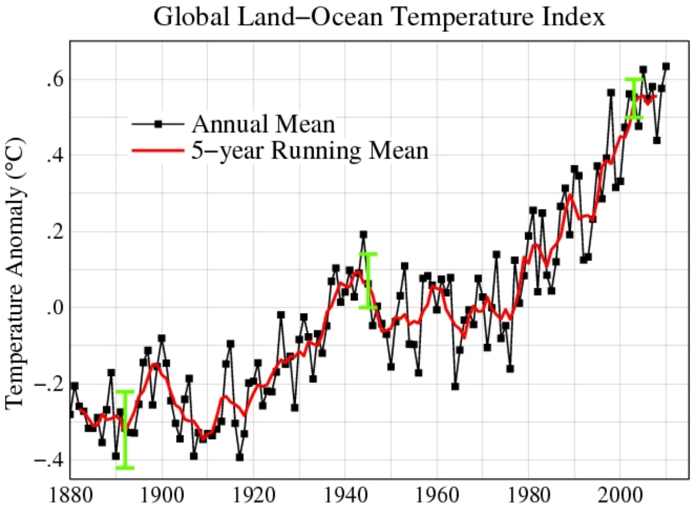


John Baez
Climate Science Seminar
California State University Northridge
April 26, 2013

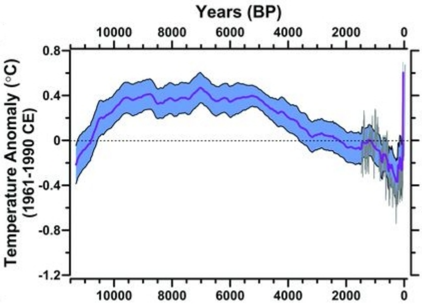
Understanding the Earth's climate poses different challenges at different time scales.

The Earth has been cooling for at least 15 million years, with glaciers in the Northern Hemisphere for at least 5 million years. Irregular climate cycles have been getting stronger during this time, becoming full-fledged **glacial cycles** roughly 2.5 million years ago. These cycles lasted roughly 40,000 years at first, and more recently about 100,000 years.

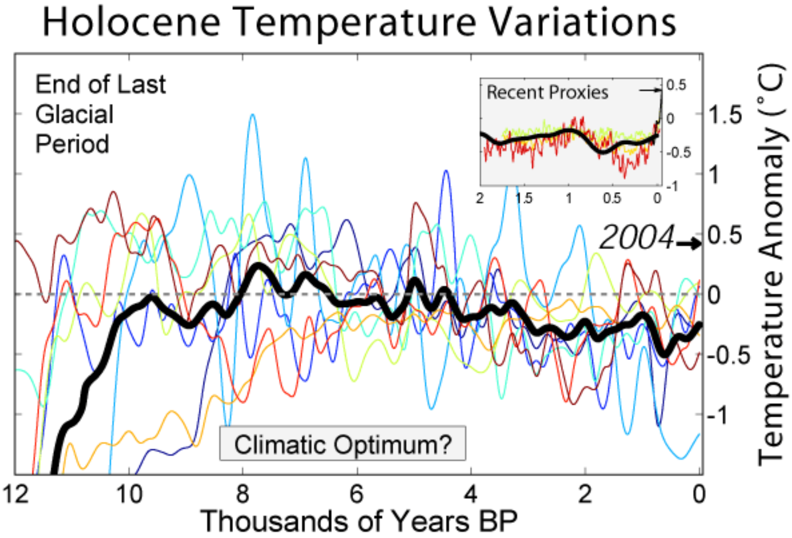
Let's zoom out and look at the climate over longer and longer periods of time!



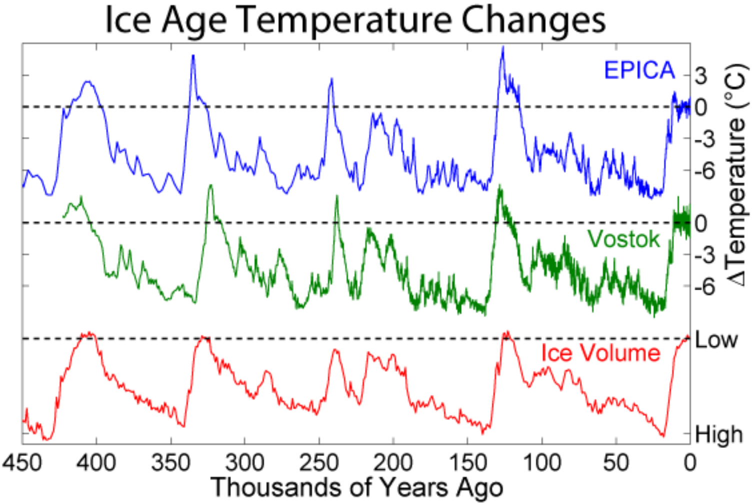
NASA Goddard Institute of Space Science



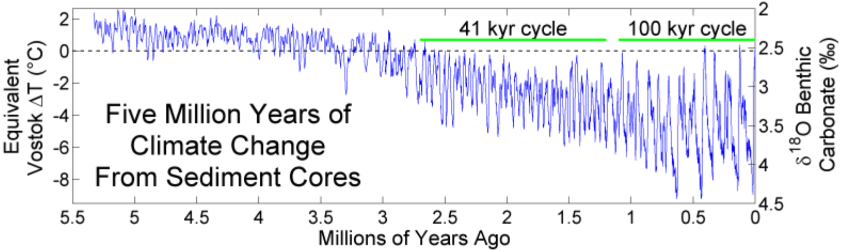
Reconstruction of temperature from 73 different records — Marcott *et al.*



8 temperature reconstructions — Global Warming Art

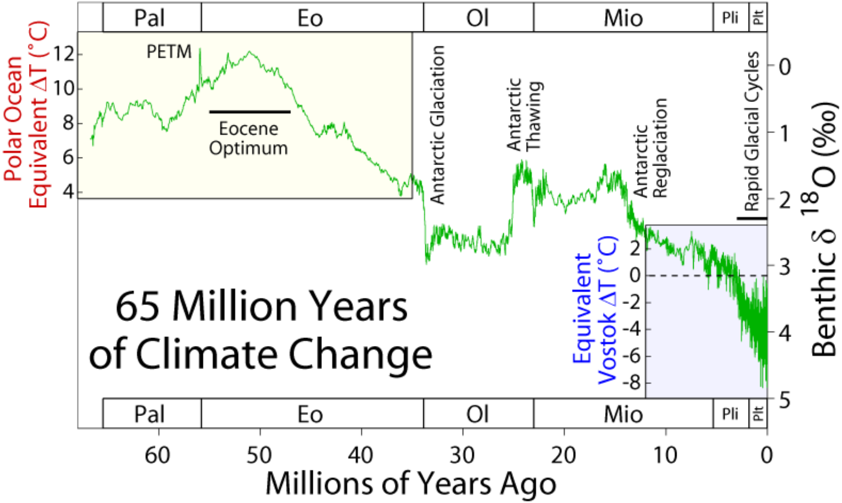


Recent glacial cycles — Global Warming Art



Oxygen isotope measurements of benthic forams, Lisiecki and Raymo

The Pliocene began 5.3 million years ago;
the Pleistocene 2.6 million years ago.



Oxygen isotope measurements of benthic forams, Zachos *et al.*

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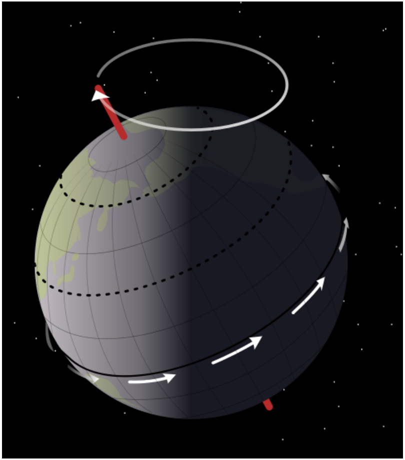
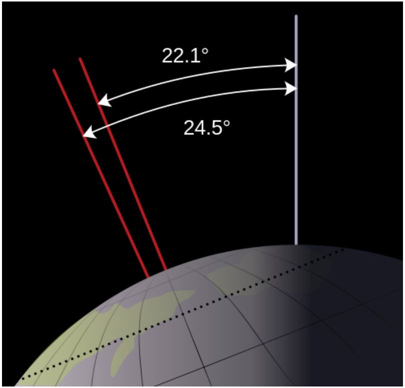
The amount of sunshine at different latitudes in different seasons varies due to changes in three of the Earth's orbital parameters:

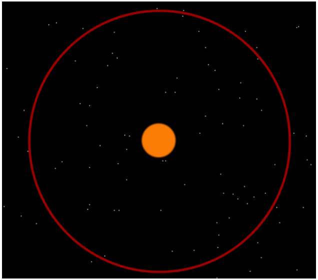
1) precession of the Earth's axis
2) changes in the amount of the Earth's axial tilt
3) changes in the eccentricity of the Earth's orbit.

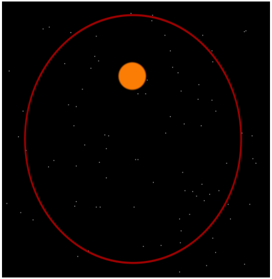


Precession has a period of roughly 23,000 years. In fact there are different components to this variation, with periods of 19, 22, and 24 kiloyears.



The Earth's obliquity or axial tilt varies with a period of 41 kiloyears.





The eccentricity of the Earth's orbit changes in cycles with several components, with periods of 413 kiloyears (the strongest), 125 kiloyears, and 95 kiloyears.

The orbit varies from almost circular to having an eccentricity of 0.06 (vastly exaggerated at right).

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However, these changes dramatically affect the amount of sunshine hitting the Earth at a *given time of year* at a *given latitude*. On the summer solstice at 65° N, averaged over the whole day, the insolation can vary between 440 and 560 watts per square meter!

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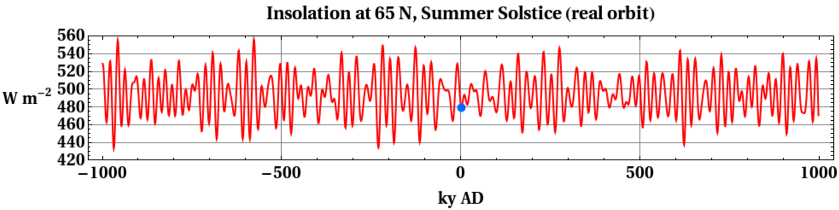
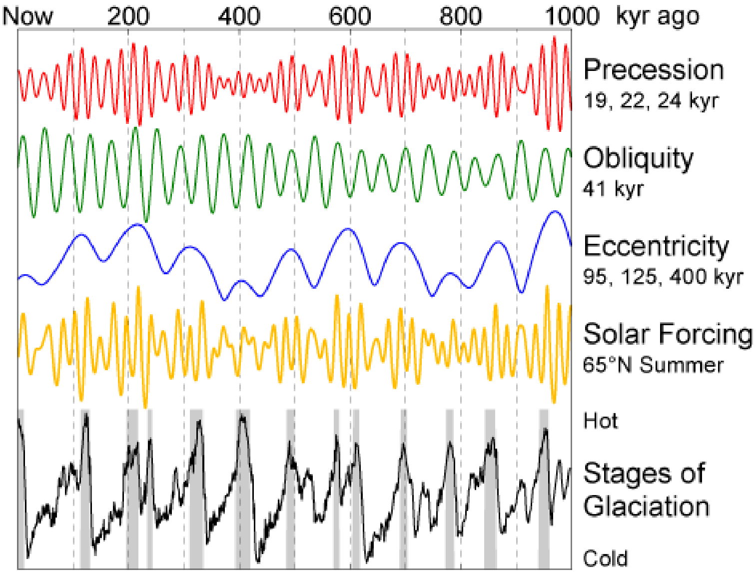
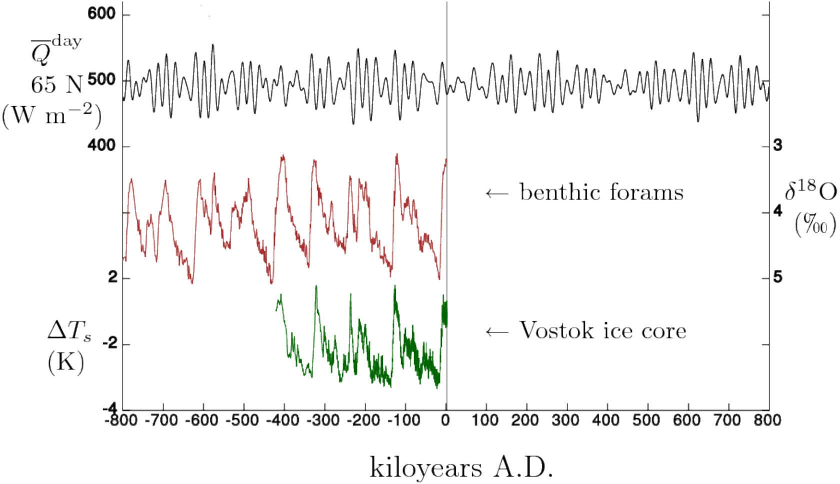


Unfortunately, comparing this summer solstice insolation at 65° N to the Earth's glacial cycles, we do *not* say **"Aha, now the glacial cycles make perfect sense!"**


Now
200
400
600
800
1000
kyr ago
Precession
19, 22, 24 kyr
Obliquity
41 kyr
Eccentricity
95, 125, 400 kyr
Solar Forcing
65°N Summer
Hot
Stages of Glaciation
Cold



$\overline{Q}^{\text{day}}$
65 N
(W m^{-2})
600
500
400
2
-2
-4
ΔT_s
(K)
3
4
5
δ^{18}O
(‰)
← benthic forams
← Vostok ice core
-800 -700 -600 -500 -400 -300 -200 -100 0 100 200 300 400 500 600 700 800
kiloyears A.D.

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But my student Blake Pollard decided to try it as a little warmup project, which he published on my blog. So let's look at what he found.

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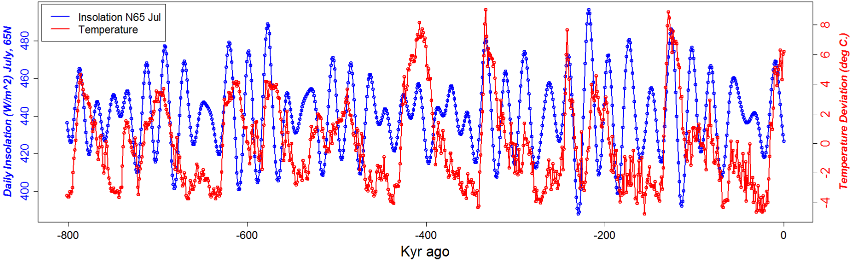
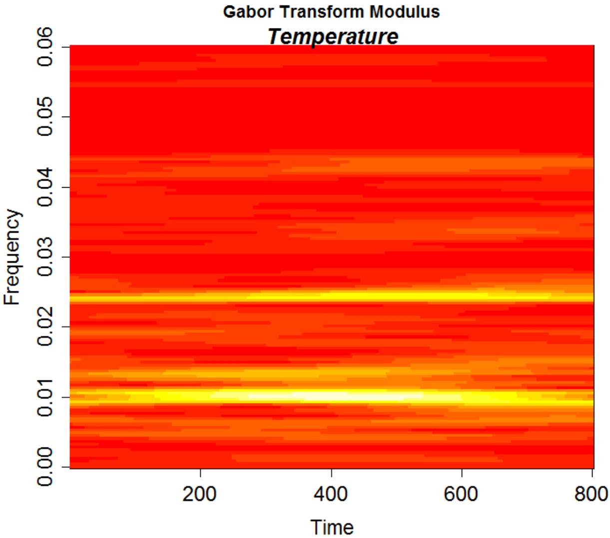
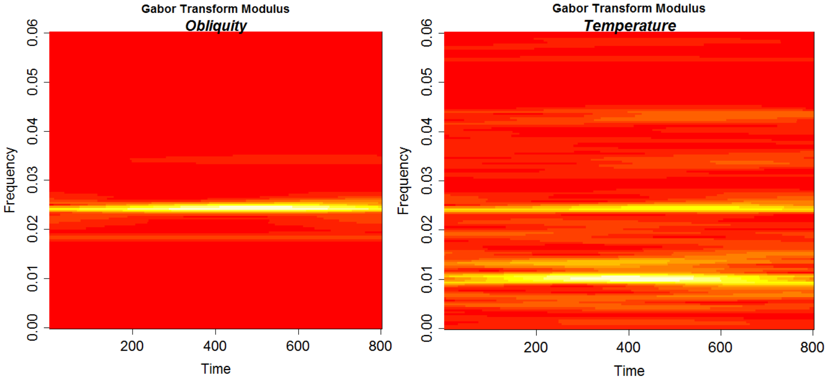
Pollard compared the Earth's insolation on July 1st at 65° N as computed by André Berger to the Earth's temperature as estimated using deuterium concentrations in an ice core from the Antarctic site EPICA Dome C. Merely graphing them together, we get a mess:



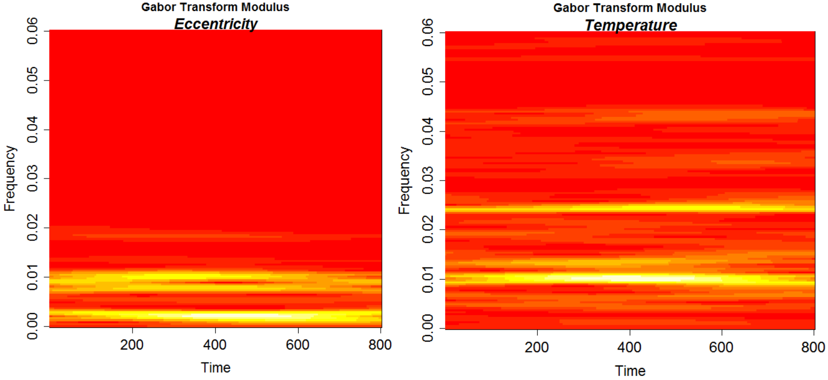
Then he took a windowed Fourier transform or 'Gabor transform' of the temperature data. This shows how the dominant frequencies of the temperature variations change with time. The yellow means a strong signal at this frequency (in inverse kiloyears):



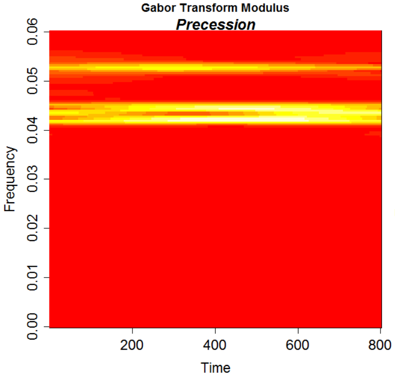
He compared this to obliquity, which has a peak at period 41 kiloyears, so frequency 0.024 kiloyears^{-1}:

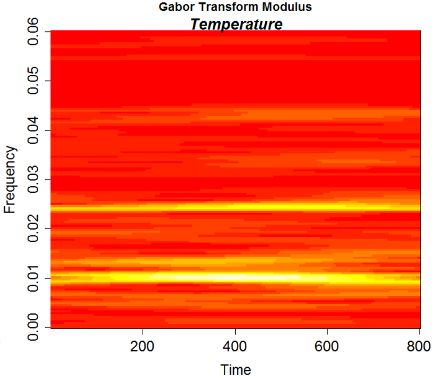


He compared it to eccentricity, which has peaks at periods of 413, 125, and 95 kiloyears, so frequencies of 0.0024, 0.008, and 0.011 kiloyears^{-1}:

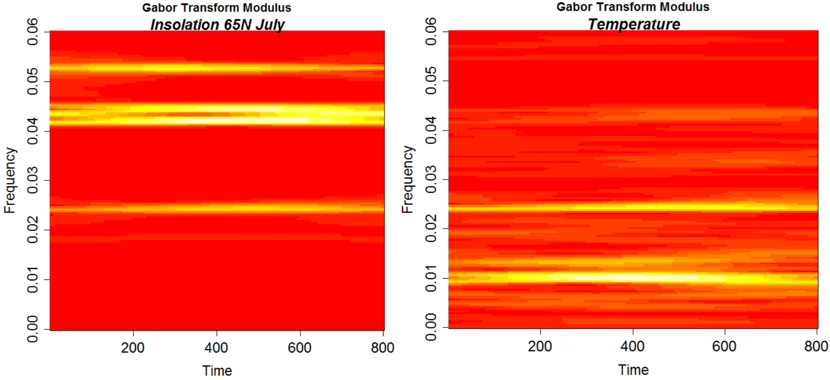


He also compared it to precession, which has peaks at periods of 19, 22, and 24 kiloyears, so frequences of 0.052, 0.045 and 0.042 kiloyears^{-1}:





He also compared it to insolation on July 1st at 65° N:



So: it looks as if in the last 800,000 years, variations in the Earth's temperature occur at periods that most closely match those of *obliquity* (41 kiloyear) and *eccentricity* ($\sim$100 kiloyear) cycles.

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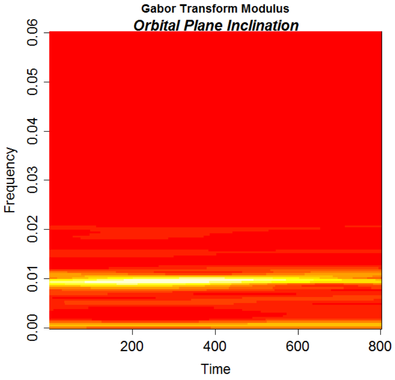
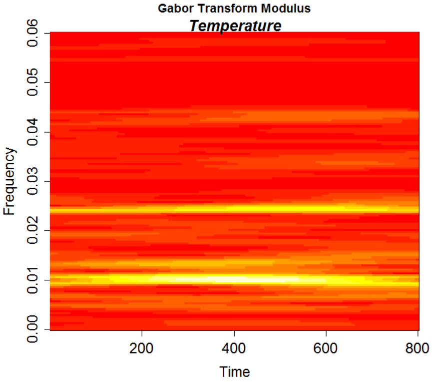
All this agrees with the conventional wisdom. But there are alternative theories...

Richard Muller and Gordan MacDonald argue that glacial cycles are correlated to the angle between the plane of the Earth's orbit and the plane perpendicular to the angular momentum of the Solar System. So Pollard looked at this too:





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This leads us to our next point...

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In a 1998 letter in *Nature*, Didier Paillard proposed two models. I'll only present the simpler, qualitative model.

In this simple model, the Earth can be in three different states:

- **i**: interglacial
- **g**: mild glacial
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- **g**: mild glacial
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Moreover:

- The Earth goes from **i** to **g** as soon as the insolation goes below some level i_0.
- The Earth goes from **g** to **G** when the insolation goes below some level i_2, if it has remained below i_3 for at least a time t_g.
- The Earth goes from **G** to **i** as soon as the insolation goes above some level i_1.

Only the transitions $\mathbf{i} \to \mathbf{g}$, $\mathbf{g} \to \mathbf{G}$ and $\mathbf{G} \to \mathbf{i}$ are allowed! The reverse transitions are forbidden.

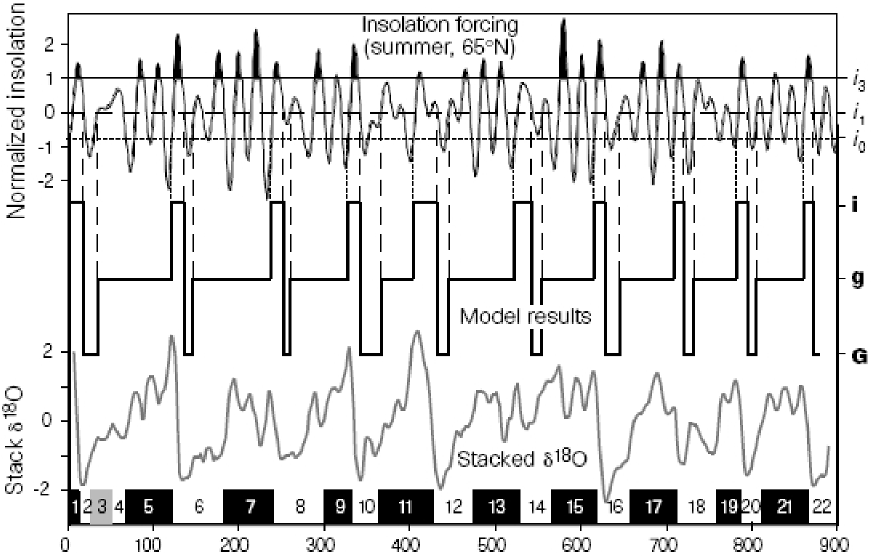
So, the only thing required to complete Paillard's model are choices of these numbers:

$$i_0 = -0.75, \qquad i_1 = i_2 = 0, \qquad i_3 = 1$$

where insolation is measured in standard deviations from its mean value, and

$$t_g = 33 \text{ kiloyears}$$

which is longer than a precession cycle. His model then gives these results:



Insolation forcing
(summer, 65°N)
Normalized insolation
2
1
0
-1
-2
i_3
i_1
i_0
i
g
G
Model results
Stacked $\delta^{18}O$
Stack $\delta^{18}O$
2
0
-2
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
0
100
200
300
400
500
600
700
800
900

So, a very simple model can give qualitatively correct predictions for the last million years!

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• • •

This has been a very quick introduction to a complex field — a field I'm not an expert in.

I mainly hoped to convince you that there are many interesting problems here. They may be important for understanding abrupt climate change.