Title: A Movable Trigger: Fossil fuel CO2 and the Next Glaciation

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Abstract:

A Movable Trigger

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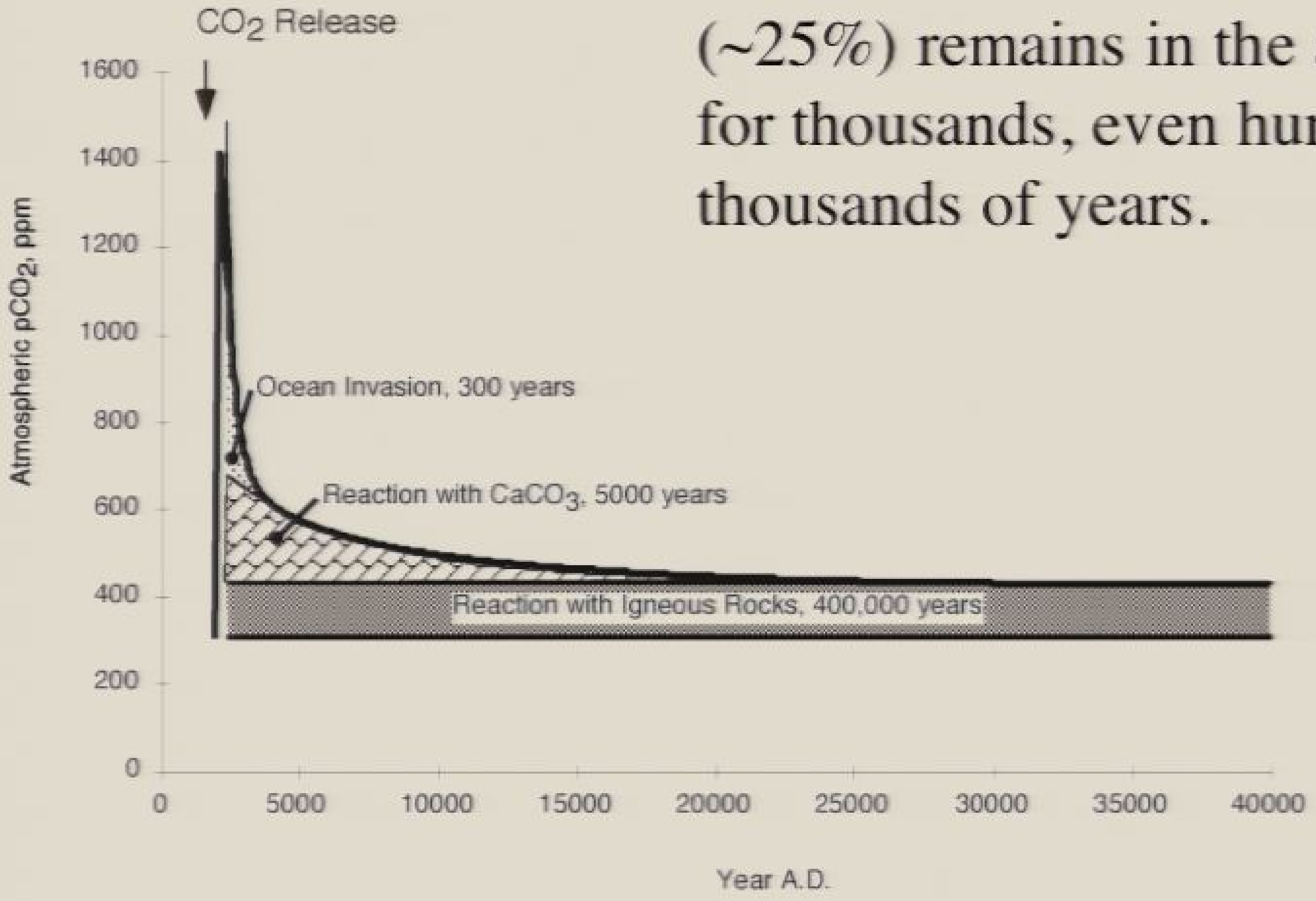
Fossil fuel CO_2 and the Next Glaciation

I. Fate of fossil fuel CO_2

Dissolves in the ocean	(centuries)
Uptake / release from terrestrial biosphere	(centuries)
Neutralization by $CaCO_3$	(5-10 kyr)
Lithification by weathering of silicate rocks	(400 kyr)

Most of the CO_2 goes away in a few centuries, but a fraction (~25%) remains in the atmosphere for thousands, even hundreds of thousands of years.



Archer, 1997 and 2005

IPCC 2001 got this wrong

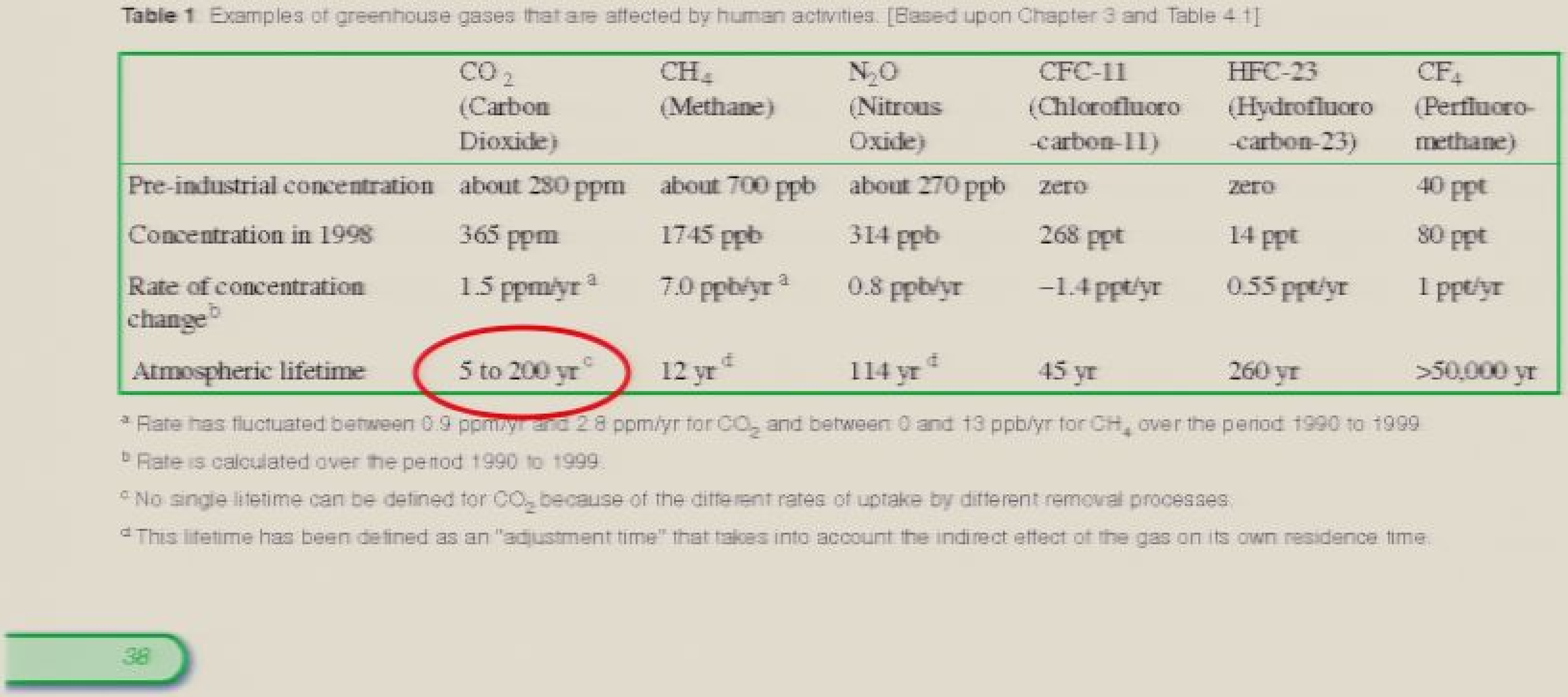


Table 1 Examples of greenhouse gases that are affected by human activities. [Based upon Chapter 3 and Table 4.1]

	CO_2 (Carbon Dioxide)	CH_4 (Methane)	N_2O (Nitrous Oxide)	CFC-11 (Chlorofluoro-carbon-11)	HFC-23 (Hydrofluoro-carbon-23)	CF_4 (Perfluoro-methane)
Pre-industrial concentration	about 280 ppm	about 700 ppb	about 270 ppb	zero	zero	40 ppt
Concentration in 1998	365 ppm	1745 ppb	314 ppb	268 ppt	14 ppt	80 ppt
Rate of concentration change[b]	1.5 ppm/yr [a]	7.0 ppb/yr [a]	0.8 ppb/yr	−1.4 ppt/yr	0.55 ppt/yr	1 ppt/yr
Atmospheric lifetime	5 to 200 yr [c]	12 yr [d]	114 yr [d]	45 yr	260 yr	>50,000 yr

[a] Rate has fluctuated between 0.9 ppm/yr and 2.8 ppm/yr for CO_2 and between 0 and 13 ppb/yr for CH_4 over the period 1990 to 1999.

[b] Rate is calculated over the period 1990 to 1999.

[c] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.

[d] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

Since then, it's repeated everywhere

Airborne Fraction of a large CO_2 release

	Peak	1 kyr	10 kyr
Archer 2005	60%	33%	15%
Lenton 2006	67-75%	14-16%	10-15%
Brovkin in prep.	67%	57%	26%
Goodwin subm.	50%	40%	
Ridgwell subm.	50%	34%	12%
Tyrell subm.	70%	42%	21%

II. Orbits and Climate

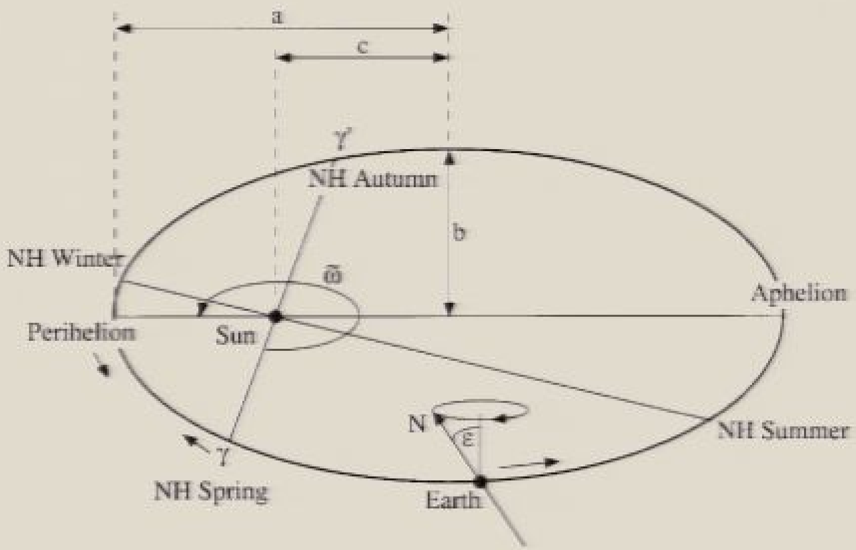
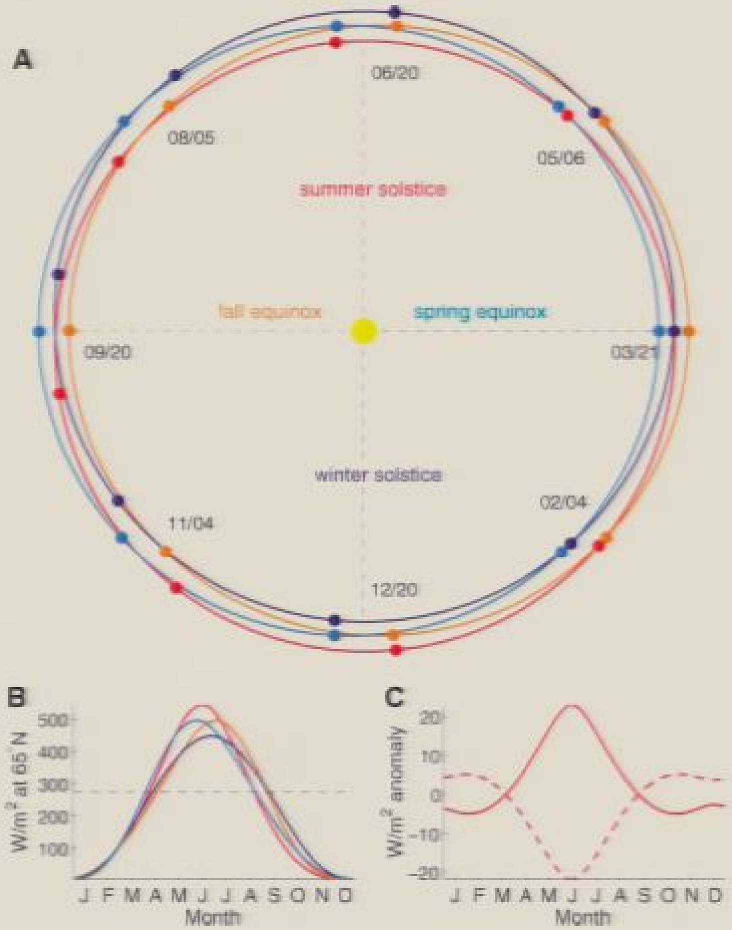


Figure 2. The orbital parameters of the Earth. Eccentricity e is defined as $e = c/a$, where a is the semimajor axis and c is the distance between the focus and the center of the ellipse. The semiminor axis b is then given by Pythagoras's theorem ($a^2 = b^2 + c^2$, which gives $b = a\sqrt{1 - e^2}$). The current eccentricity value is $e = 0.0167$, which means that the Earth's orbit is very close to a circle. The tilt of the Earth's axis with respect to the orbital plane is the obliquity ε (current value is $\varepsilon = 23.44°$). This tilt implies that the Earth equatorial plane intersects with its orbital plane, the intersection defining the $\gamma\gamma'$ line and the position of equinoxes and solstices. In the current configuration the Earth is closest to the Sun (perihelion) around January 3, just a few weeks after the Northern Hemisphere winter. This position, relative to the vernal equinox γ, is measured by the $\tilde{\omega}$ angle.

Paillard, 2001



Drawn to scale

Annual cycle of insolation at 65° N

Huybers 2006

Eccentricity

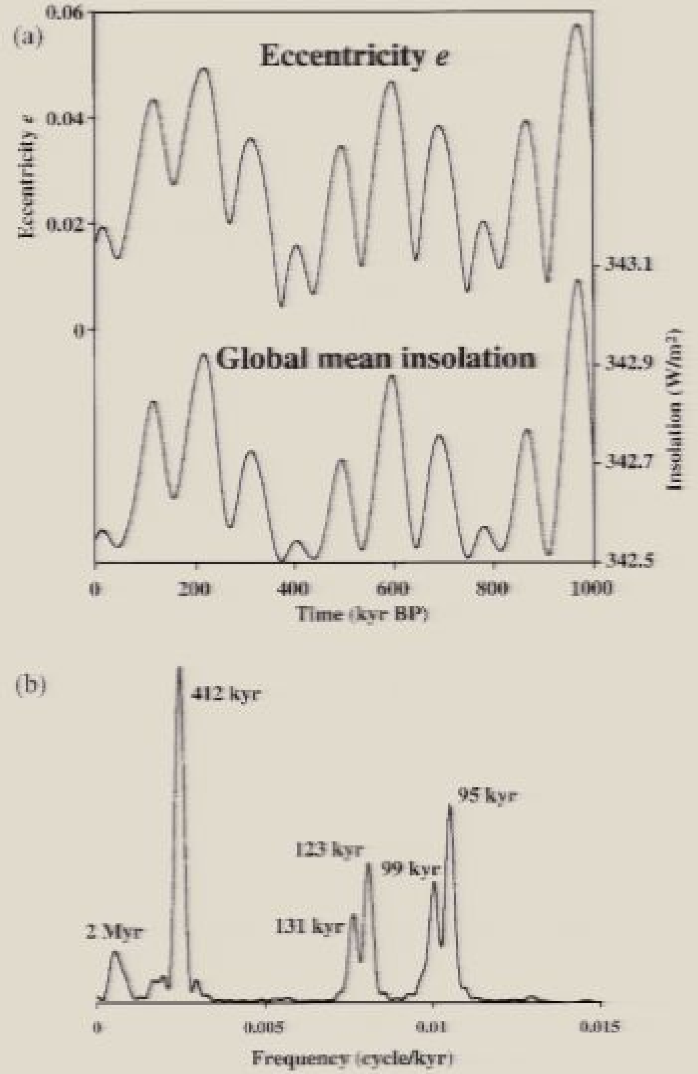


Figure 3. (a) Changes in eccentricity *e* for the last million years and its small effect on the global annual mean insolation received by the Earth (assuming a constant solar activity). (b) Spectral analysis of the eccentricity changes, revealing major periodicities at ~400 kyr and in the 100-kyr band (arbitrary vertical linear scale).

Paillard, 2001

Obliquity

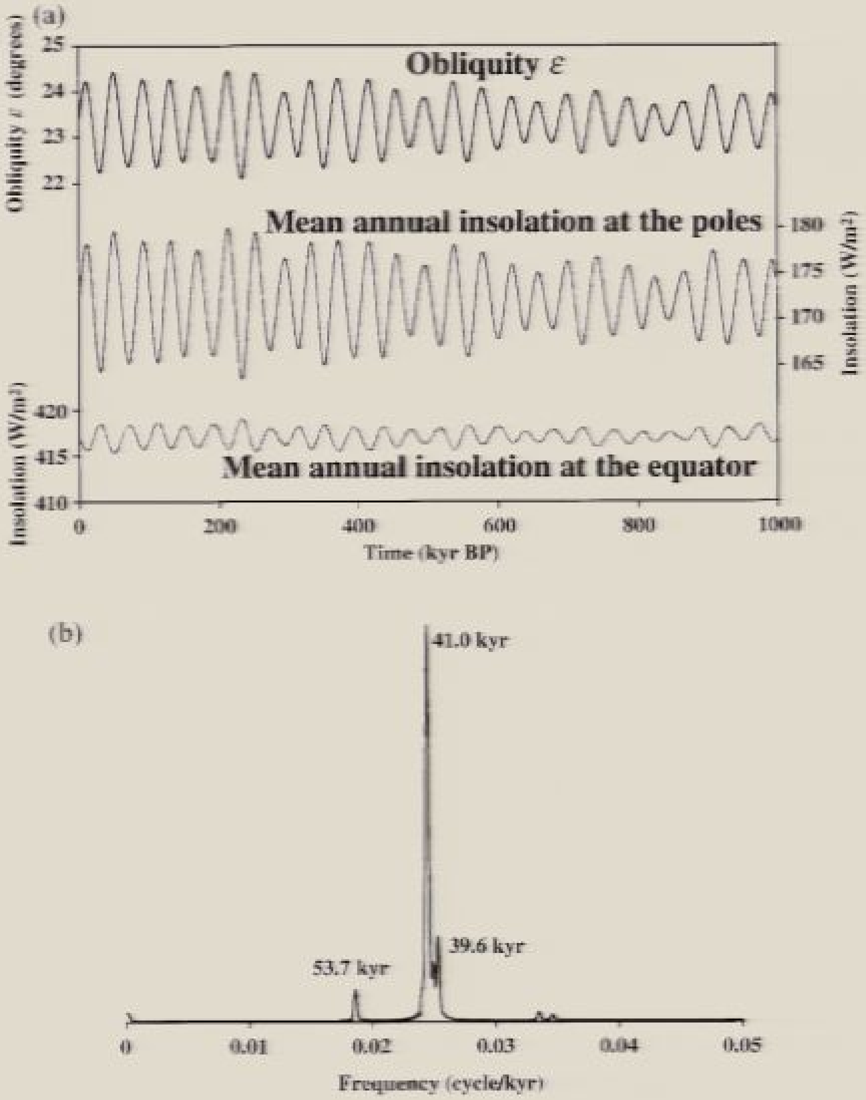


Figure 4. (a) Changes in obliquity ε for the last million years and the annual mean insolation received at the poles and at the equator. (b) Spectral analysis of the obliquity changes, revealing one major periodicity at 41 kyr (arbitrary vertical linear scale).

Paillard, 2001

Obliquity stabilized by the moon

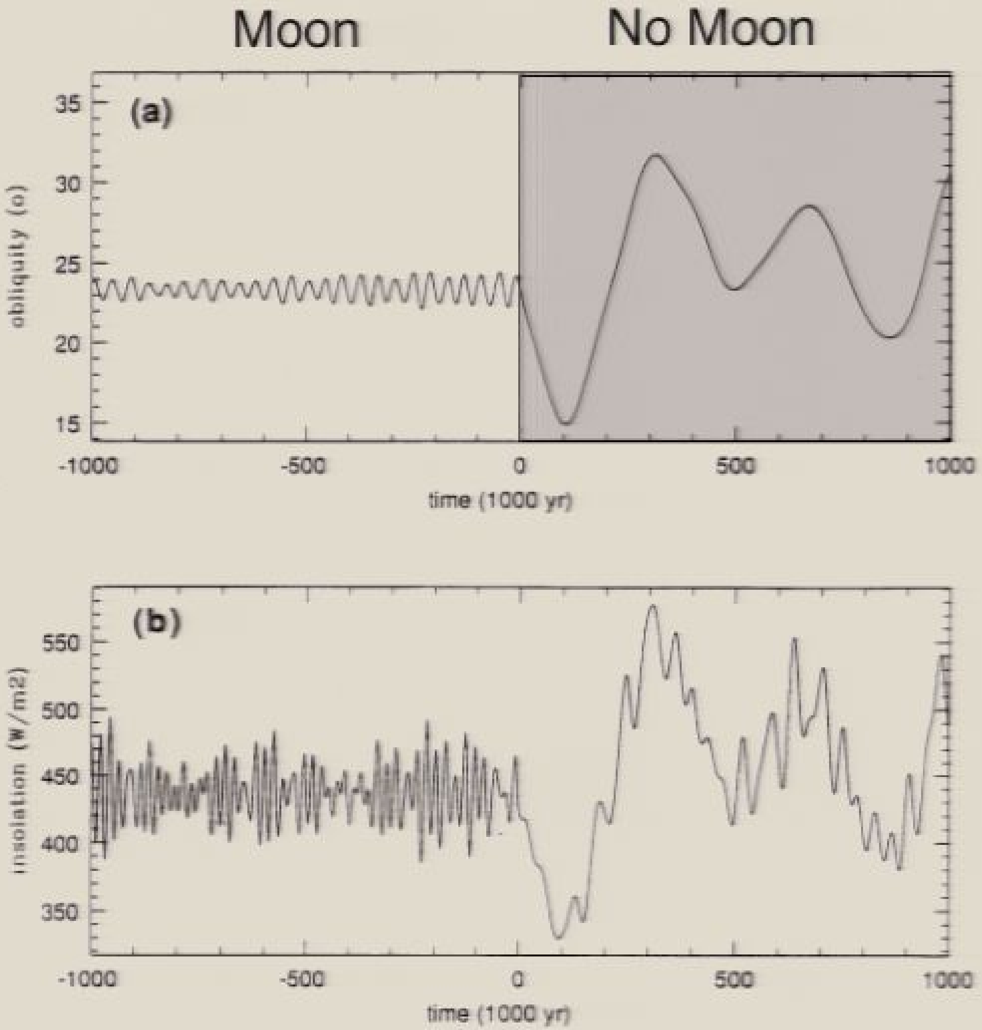
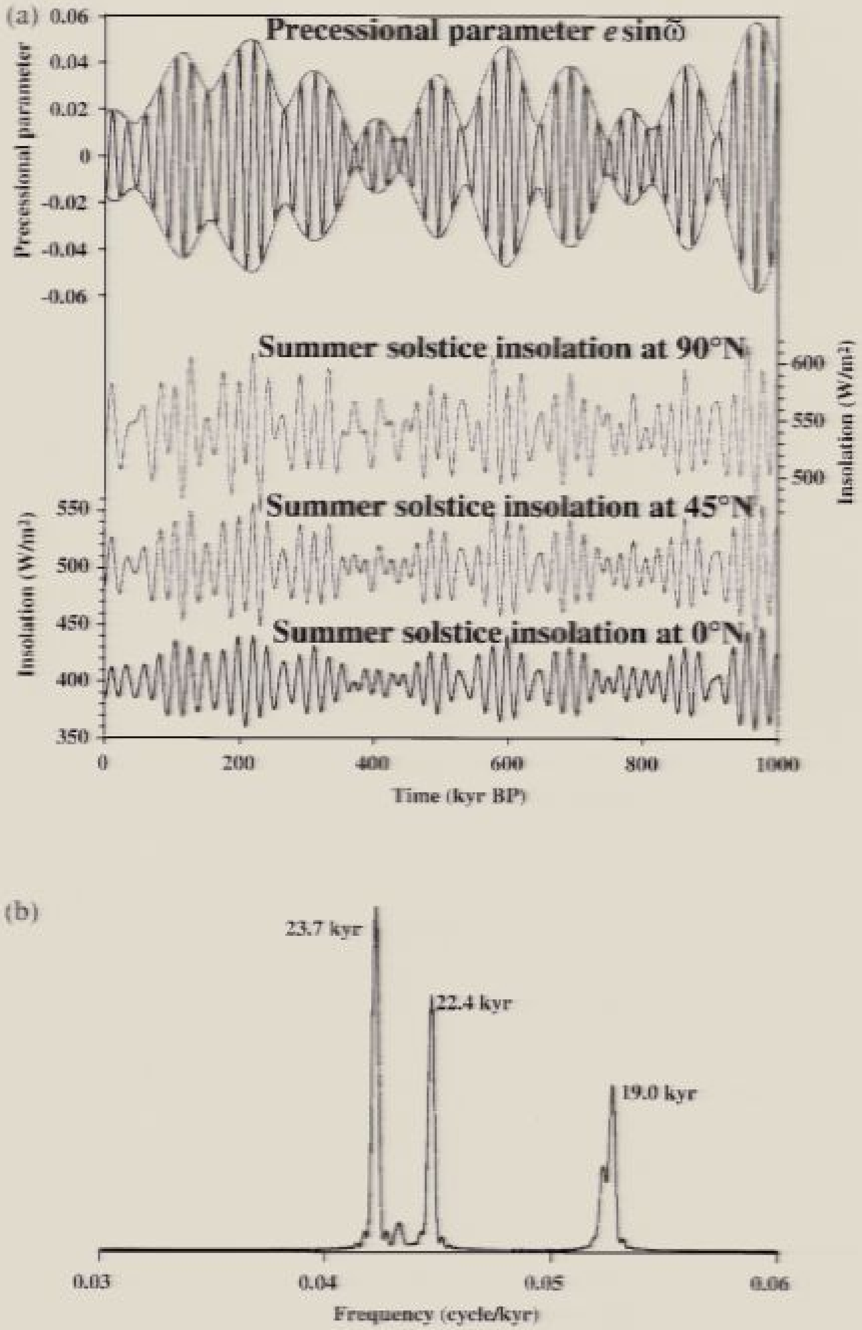


Fig. 11. Changes in obliquity (a) and insolation at 65N ($\lambda_d = 120$ deg) (b) resulting from the suppression at $t = 0$ of the Moon. The Moon is present from -1Myr to 0, and absent from 0 to +1Myr

Laskar, 1993

Precession



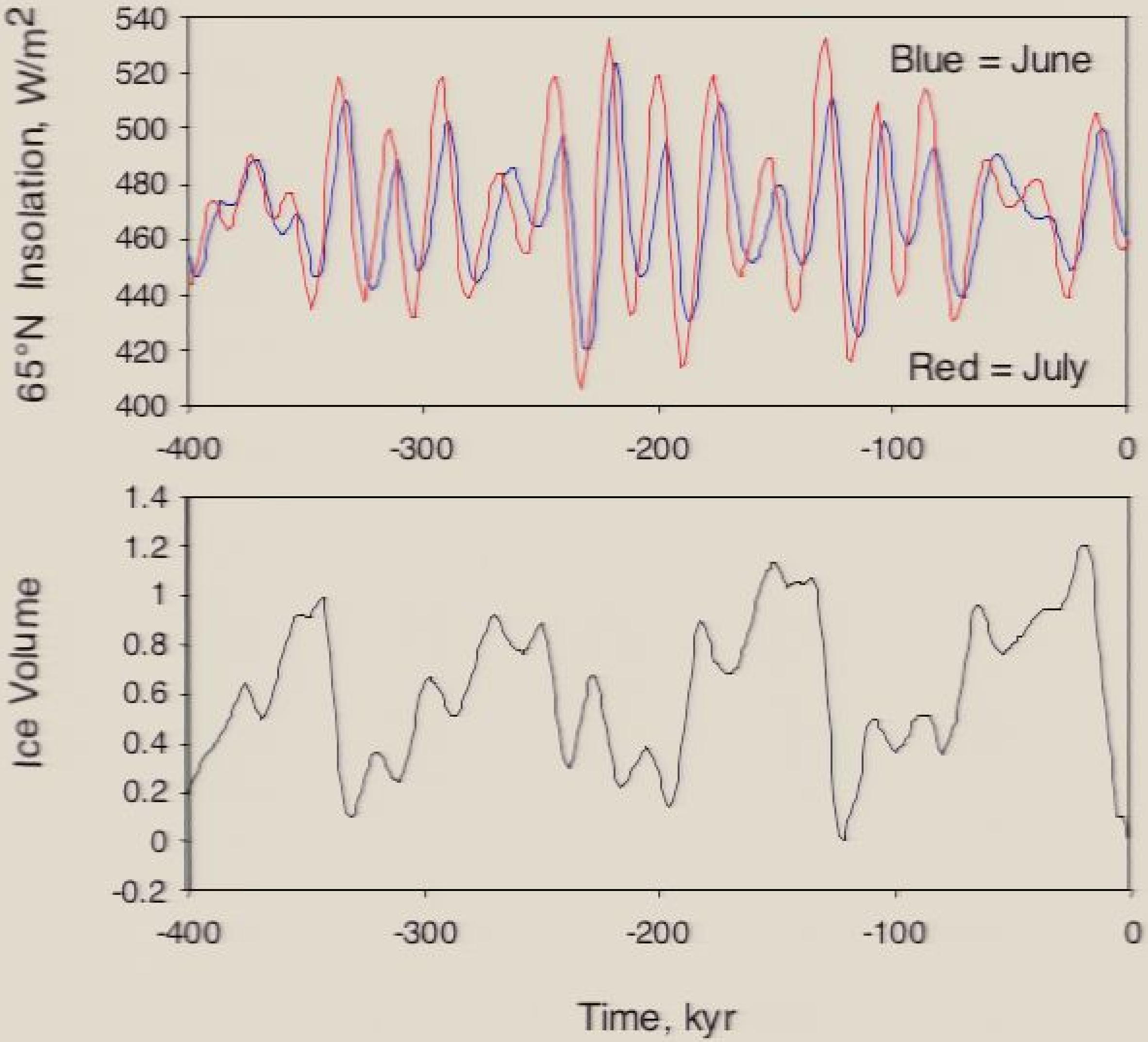
Paillard, 2001

Figure 5. (a) Changes in the precessional parameter $e \sin \tilde{\omega}$ for the last million years and the seasonal insolation received at different northern latitudes. (b) Spectral analysis of the precessional parameter changes, revealing two groups of periodicities, around 23 and 19 kyr (arbitrary vertical linear scale).

Orbital forcing and ice volume

Mostly precession.

Ice volume is
chunkier
than insolation



The spectrum of $\delta^{18}0$

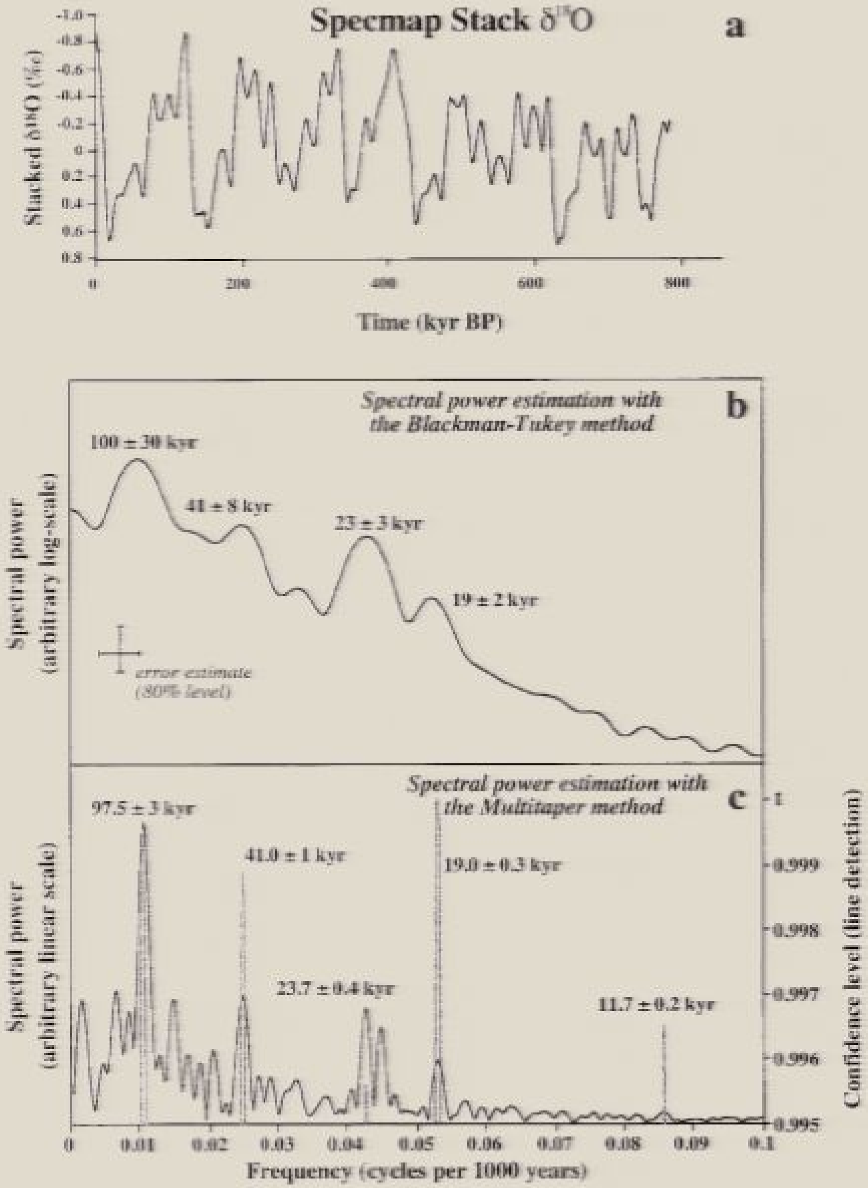


Figure 6. (a) The spectral mapping and prediction (SPECMAP) record [*Imbrie et al.*, 1984]. (b) Spectral analysis of SPECMAP using the standard Blackman-Tukey method. (c) The same analysis with the multitaper method. In Figures 6b and 6c the astronomical frequencies are clearly visible. The first harmonic of the precessional frequency is also detected by the multitaper method.

δ^{18}O records a combination of ice volume and deep ocean T

Paillard, 2001

Precession and obliquity seem to work OK

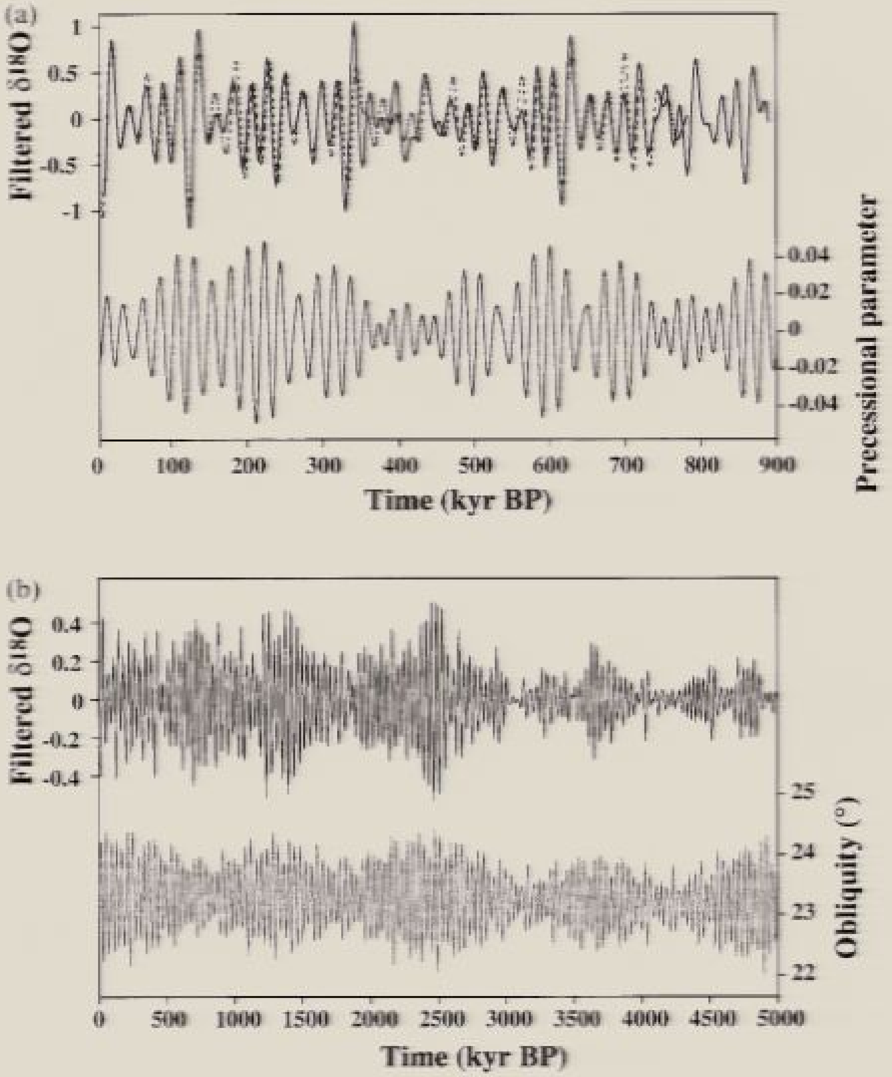
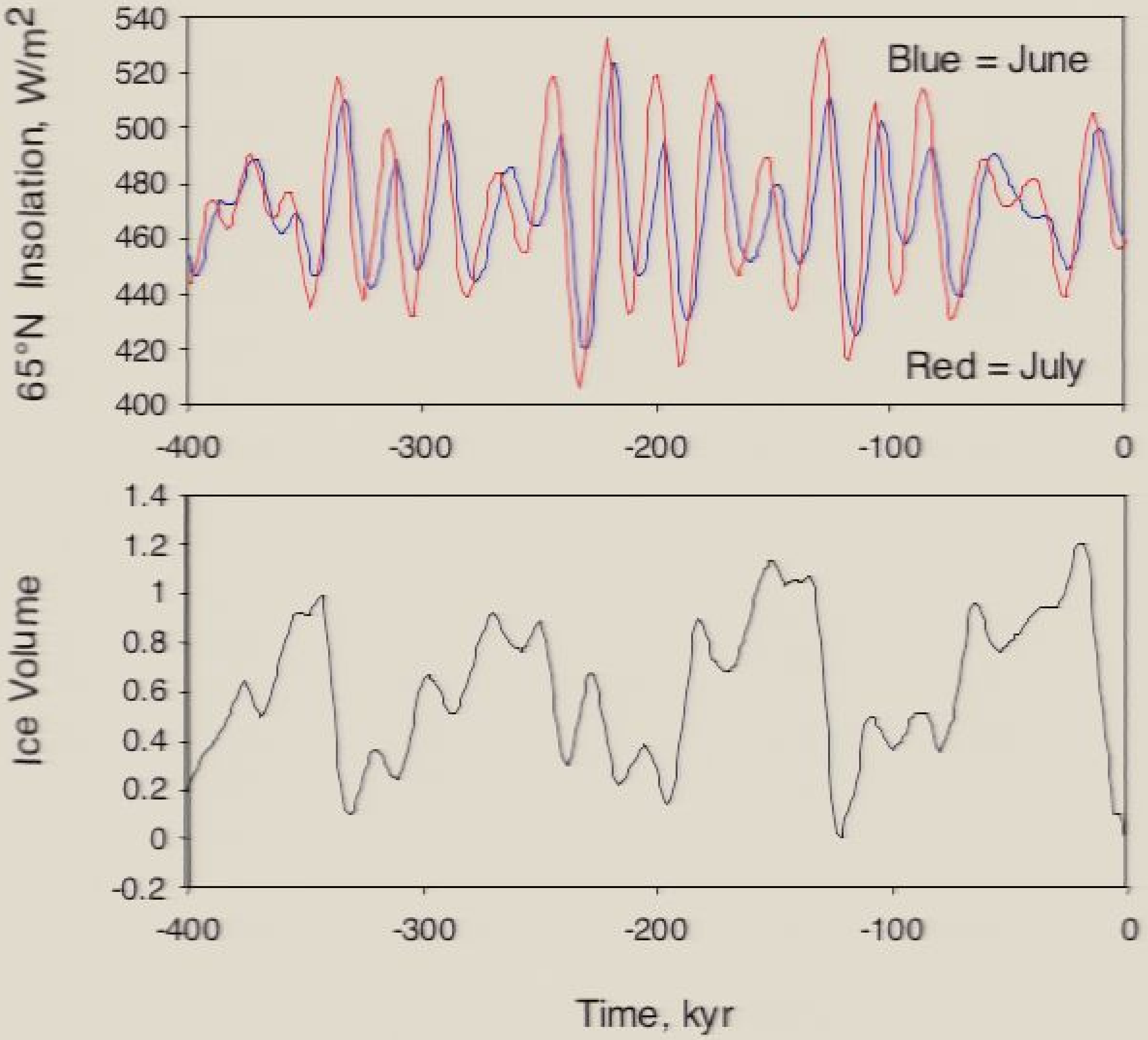


Figure 7. (a) The SPECMAP record [*Imbrie et al.*, 1984] (dashed curve) and the *Bassinot et al.* [1994b] record (bold curve) are filtered in the 23-kyr band and compared with the precessional parameter. (b) The 5-Myr long Ocean Drilling Program (ODP) 659 $\delta^{18}O$ record [*Tiedemann et al.*, 1994] is filtered in the 41-kyr band and compared with obliquity. The amplitude modulation of both the 23-kyr and the 41-kyr cyclicity appears very similar in the astronomical forcing and in the paleoclimatic record. This is probably the strongest argument in favor of a simple quasi-linear relationship between the climatic system and insolation forcing in these two frequency bands.

Paillard, 2001

Orbital forcing and ice volume



Mostly precession.

Ice volume is
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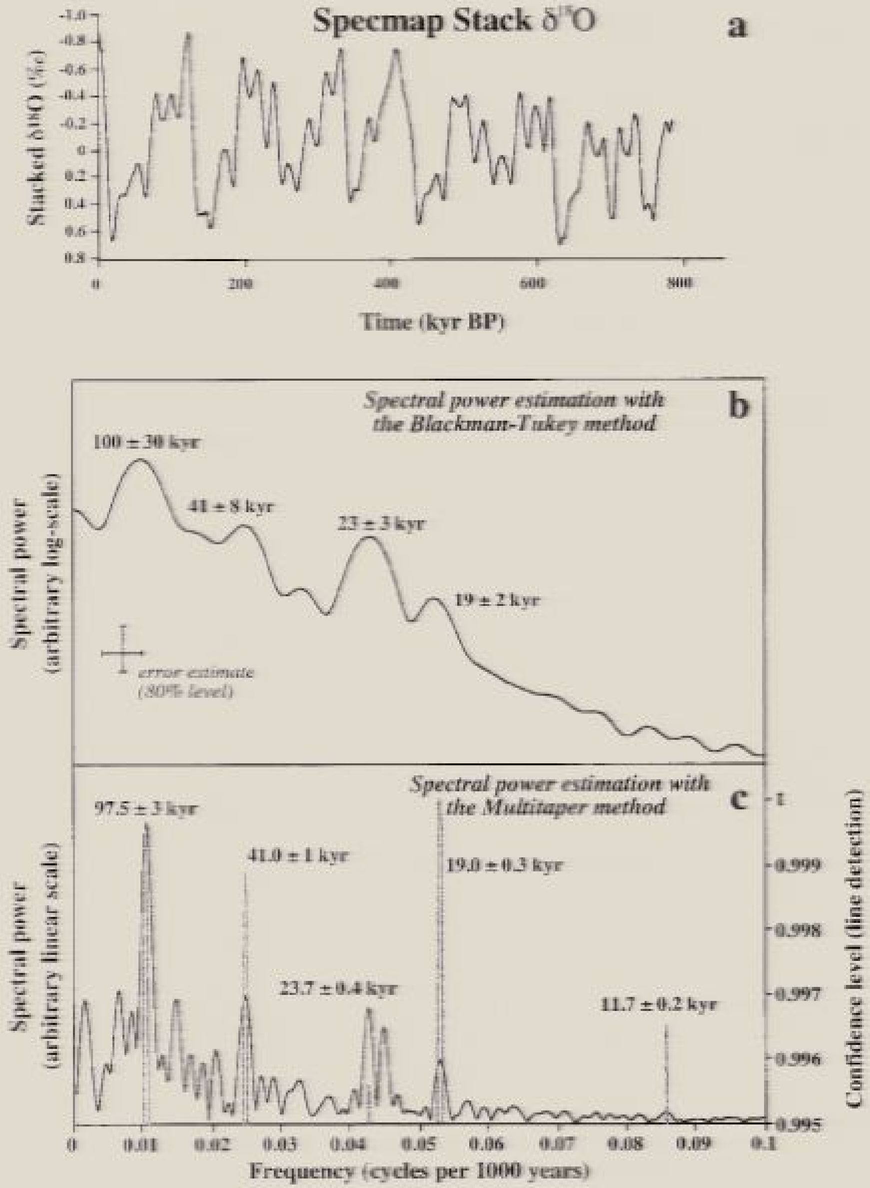
The spectrum of $\delta^{18}0$

δ^{18}O records a combination of ice volume and deep ocean T

Paillard, 2001



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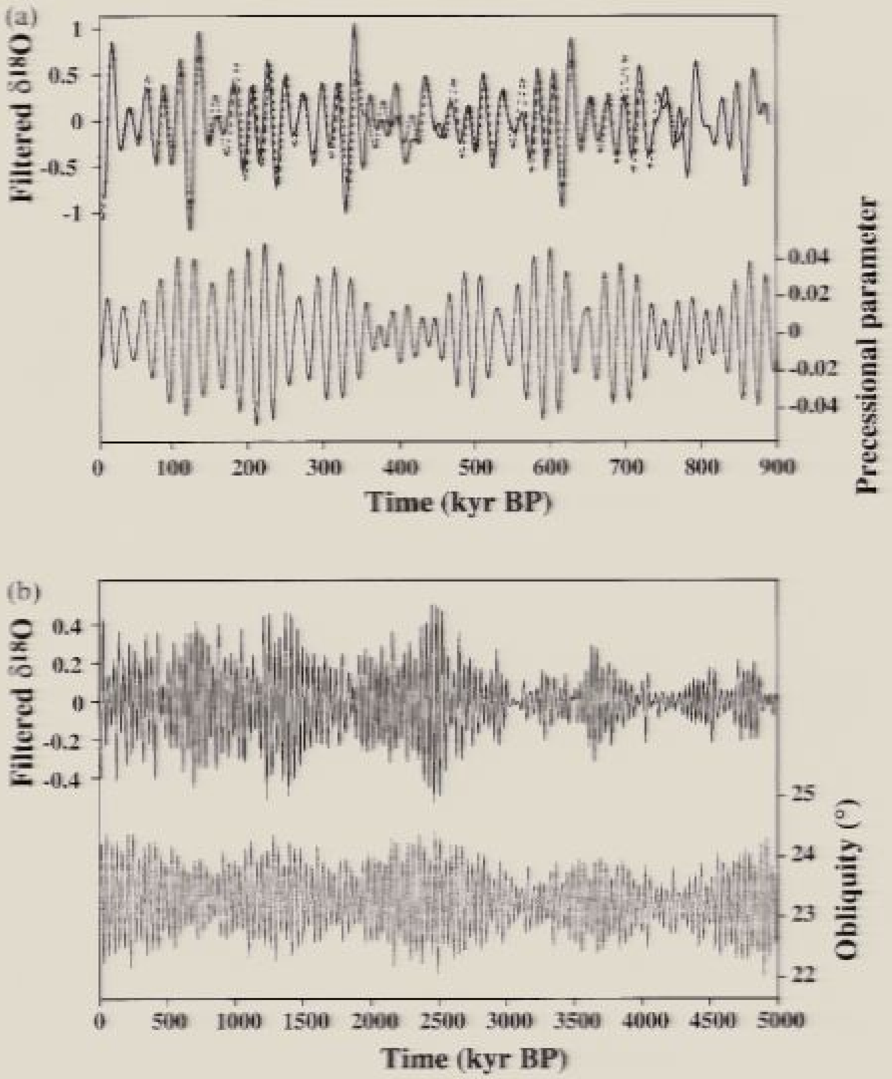

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Paillard, 2001

Eccentricity doesn’t look so terrible, either. (On the face of it).

Needs supression of the 400 kyr part

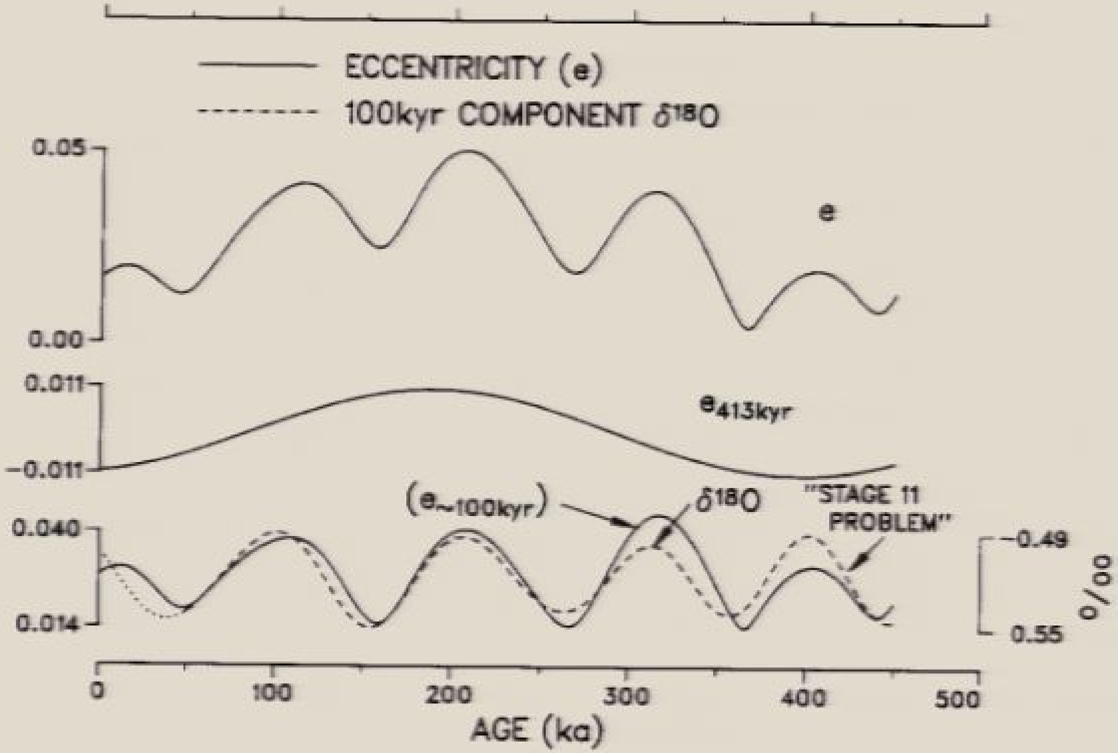
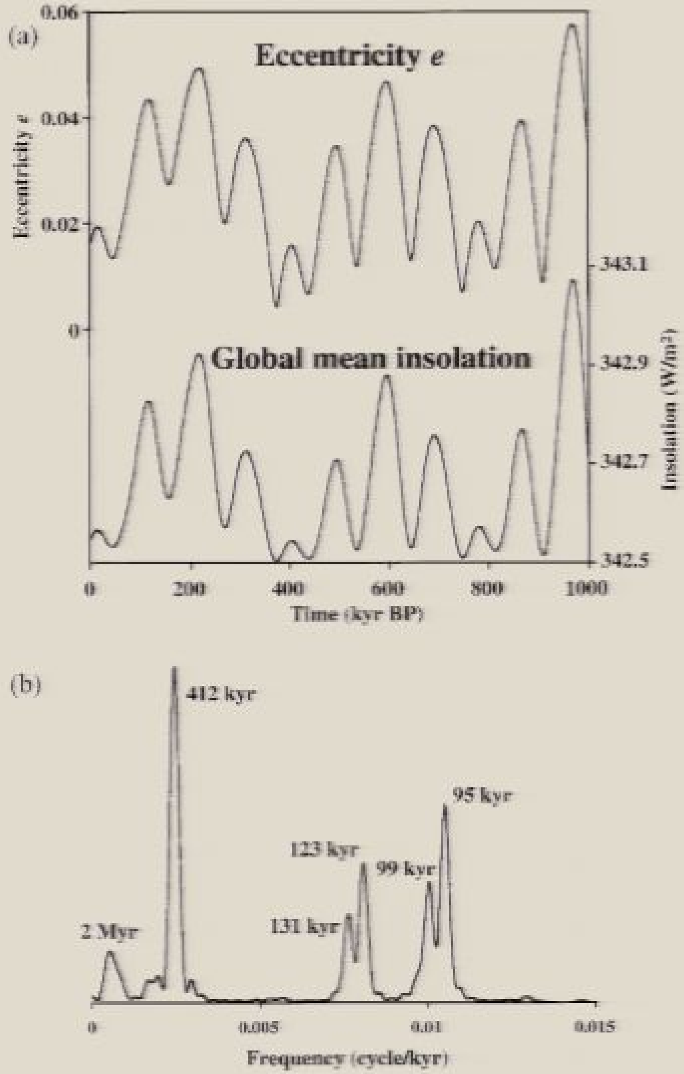


Fig. 2. Eccentricity and the 100-kyr δ^{18}O cycle. With its dominant 413-kyr component ($e_{413\ kyr}$) removed from eccentricity e, the residual signal $e_{\sim 100\ kyr}$, calculated as $e - e_{413\ kyr}$, is dominated by variance over a moderately broad band of periods near 100 kyr [Berger, 1978*a*, *b*]. Averaged over the entire interval, this part of the eccentricity signal is coherent with the 100-kyr δ^{18}O cycle and leads it systematically by ~13°. But the δ^{18}O response is not proportional to eccentricity in Stage 11.

Imbrie, 1993

Eccentricity



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Paillard, 2001

Eccentricity needs a 20x amplifier

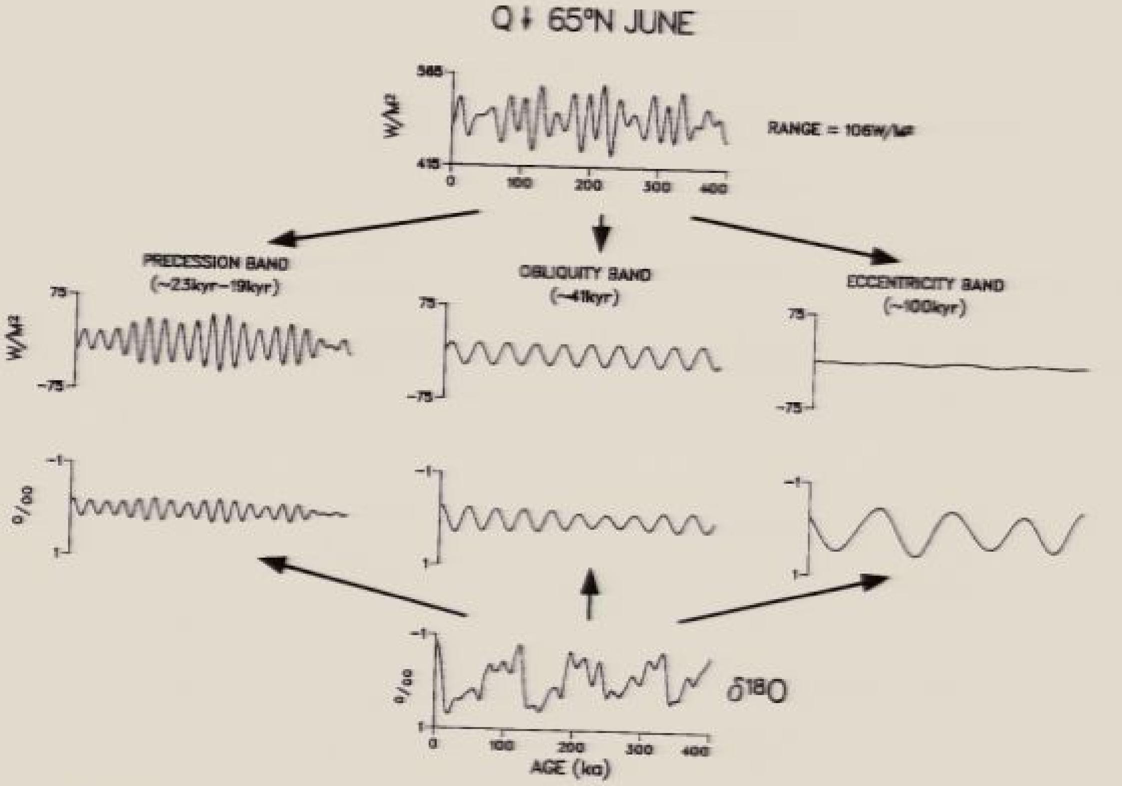


Fig. 1. The 100-kyr cycle problem as seen by partitioning radiation and climate time series into their dominant periodic components (in the precession, obliquity, and 100-kyr eccentricity bands). Radiation time series are from Berger [1978*a*]; $\delta^{18}O$ data are from Imbrie et al. [1984]. Partitioning is done using Hamming band-pass filters with a bandwidth of 0.019 kyr^{-1} for the 41- and 100-kyr bands and 0.036 kyr^{-1} for the 23-kyr band [Jenkins and Watts, 1968]. The $\delta^{18}O$ cycles at periods near 23, 41, and 100 kyr are so strongly correlated with astronomically driven radiation cycles as to suggest a causal linkage in all three bands. But these correlations for the 23-, 41-, and 100-kyr bands (coherencies of 0.95, 0.90, and 0.91, respectively, in Table 2) hide an intriguing physical problem. Why is the system's response so strong in the 100-kyr band? There the amplitude of the radiation signal ($2\ W\ m^{-2}$) is 1 order of magnitude smaller than in the other two bands.

Imbrie, 1993

The three cycles evolved independently

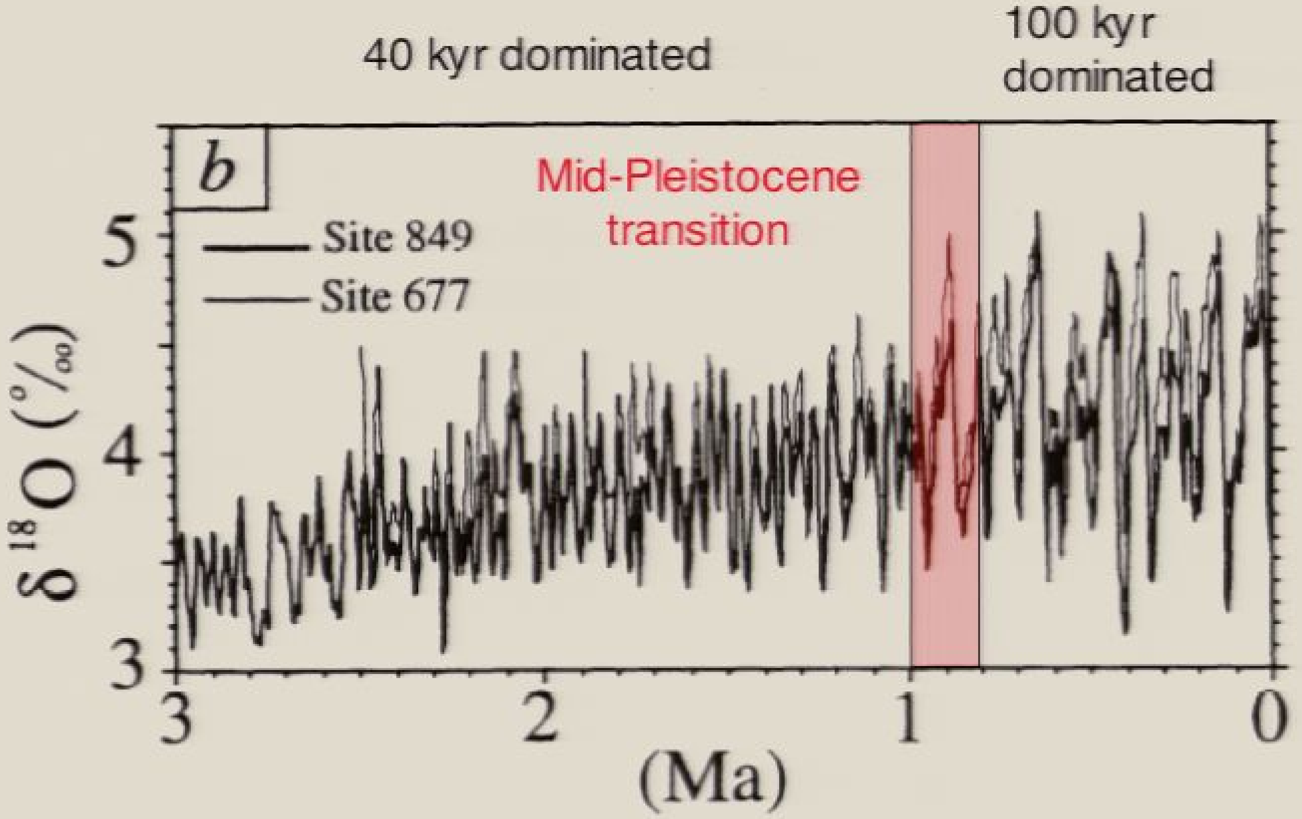


Figure 1. (a) Summer half-year insolation (in W m^{-2}) at 55°N for the last 3 Myr computed using orbital elements from *Berger and Loutre* [1991]. (b) Oxygen isotope records for Ocean Drilling Program Sites 677 and 849 over the last 3 Myr (data and age models are from *Mix et al.* [1995]).

Calder’s model

$$\frac{dV}{dt} = -k\,(i - i_0)$$

Grows if $i < i_0$, melts otherwise

k is different for growing or melting. This nonlinearity generates some 100kyr power in the output.

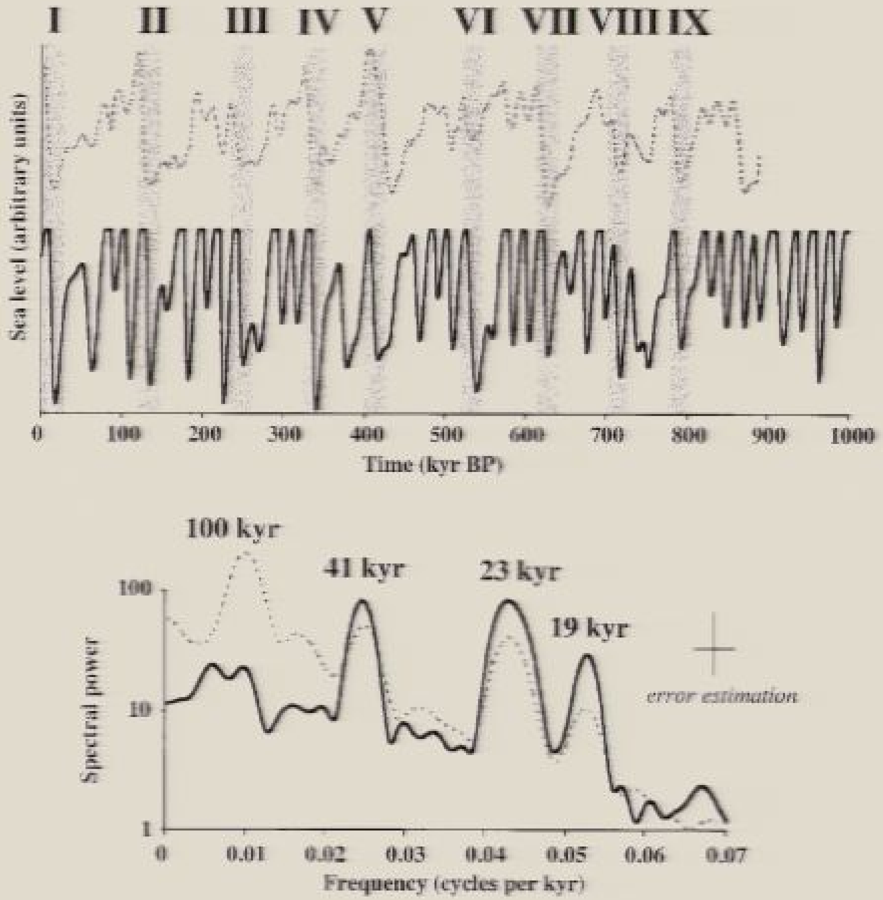
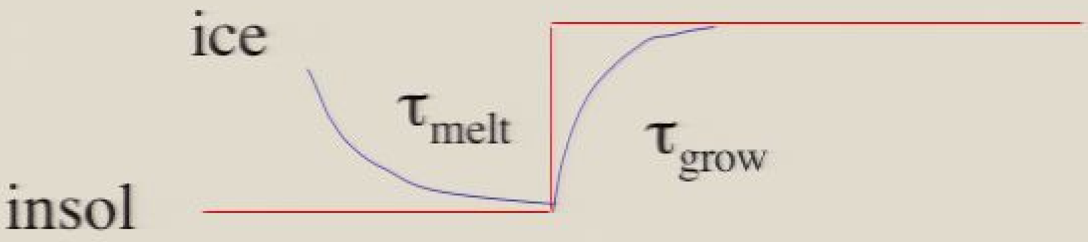


Figure 9. Results from the *Calder* [1974] model. The threshold i_0 is equal to 502 W m^{-2}, and the ratio k_A/k_M is chosen equal to 0.22. The forcing i is the summer solstice insolation at 65°N [*Laskar*, 1990]. The result is very sensitive to these choices. The agreement with the record is quite poor, but this crude model still predicts the major transitions at the right time, a feature that many, more sophisticated models do not reproduce well. An isotopic record is given here for comparison [*Bassinot et al.*, 1994b].

Paillard, 2001

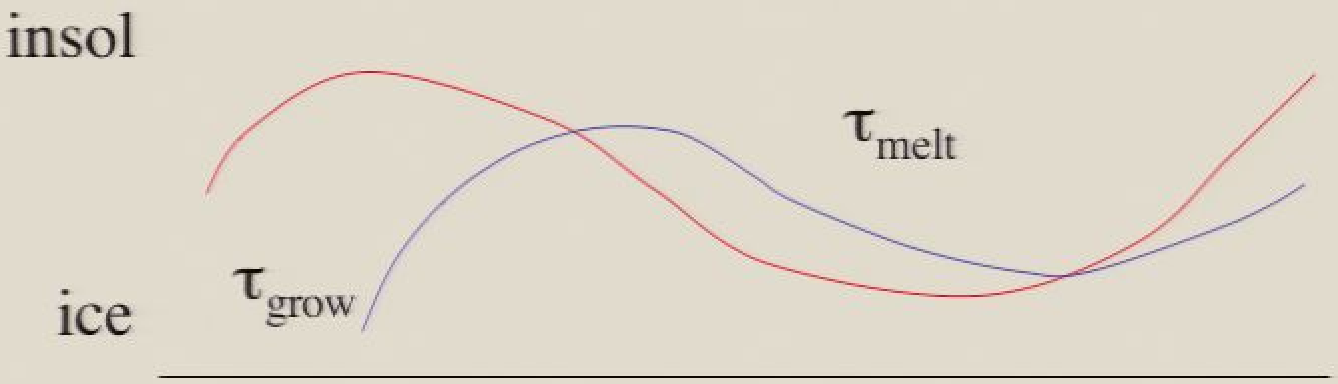
Imbrie and Imbrie model

$$\frac{dV}{dt} = \frac{(i - V)}{\tau}$$



Imbrie and Imbrie model

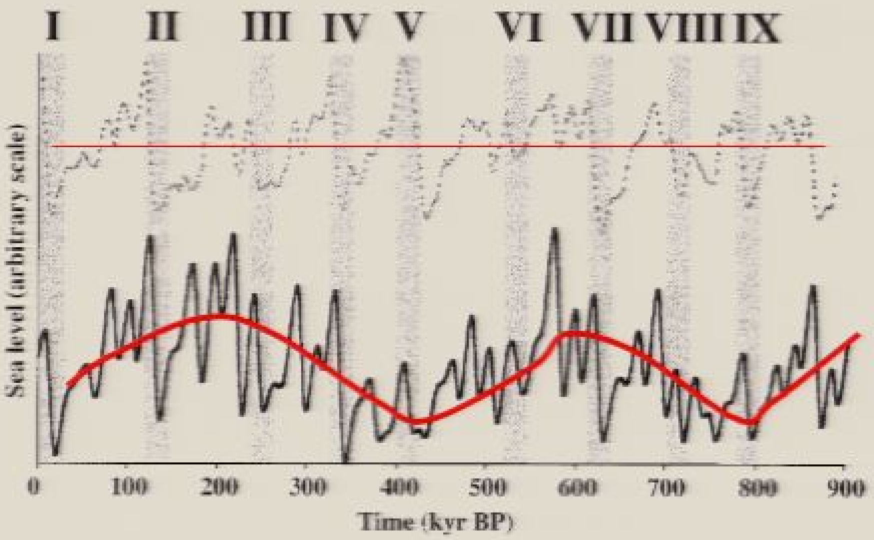
$$\frac{dV}{dt} = \frac{(i - V)}{\tau}$$



REVIEWS OF GEOPHYSICS Paillard: GLACIAL C

Imbrie and Imbrie model

Gets 100k,
but also 400k



Not there
in the data.

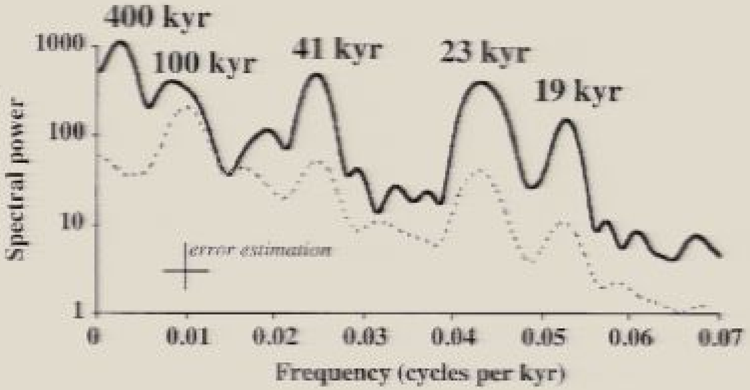


Figure 10. Same as Figure 9, but for the Imbrie model [*Imbrie and Imbrie*, 1980]. The forcing *i* is the summer solstice insolation at 65°N. The time constants are $\tau_M = 42$ kyr and $\tau_A = 10$ kyr.

Paillard threshold model

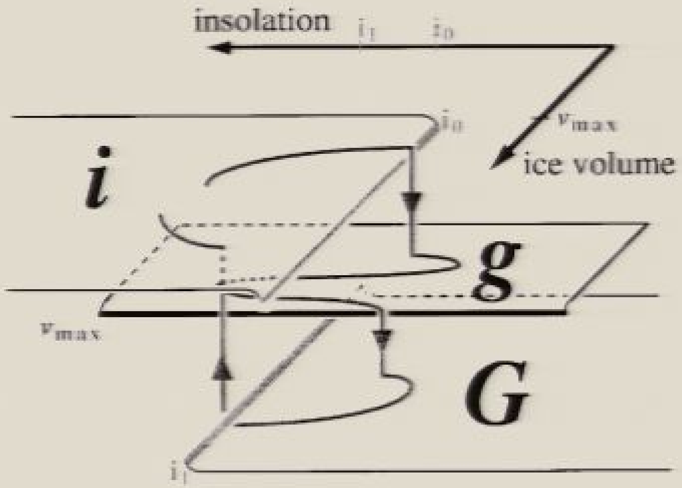
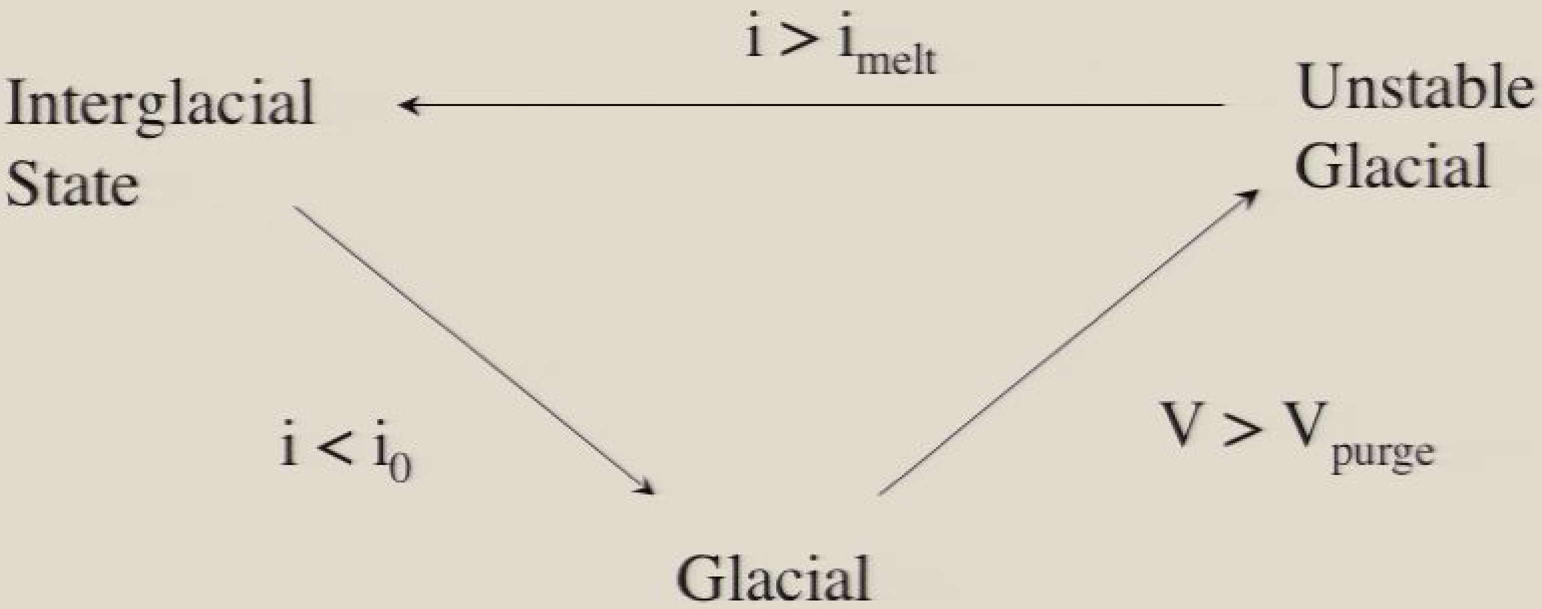


Figure 12. The threshold model. Climate is assumed to have three different regimes: i (interglacial), g (mild glacial), and G (full glacial). Transition between the regimes occurs when the insolation forcing crosses a given threshold i_0 or i_1, or when the ice volume exceeds the value v_{MAX}.

Paillard model



Interglacial State

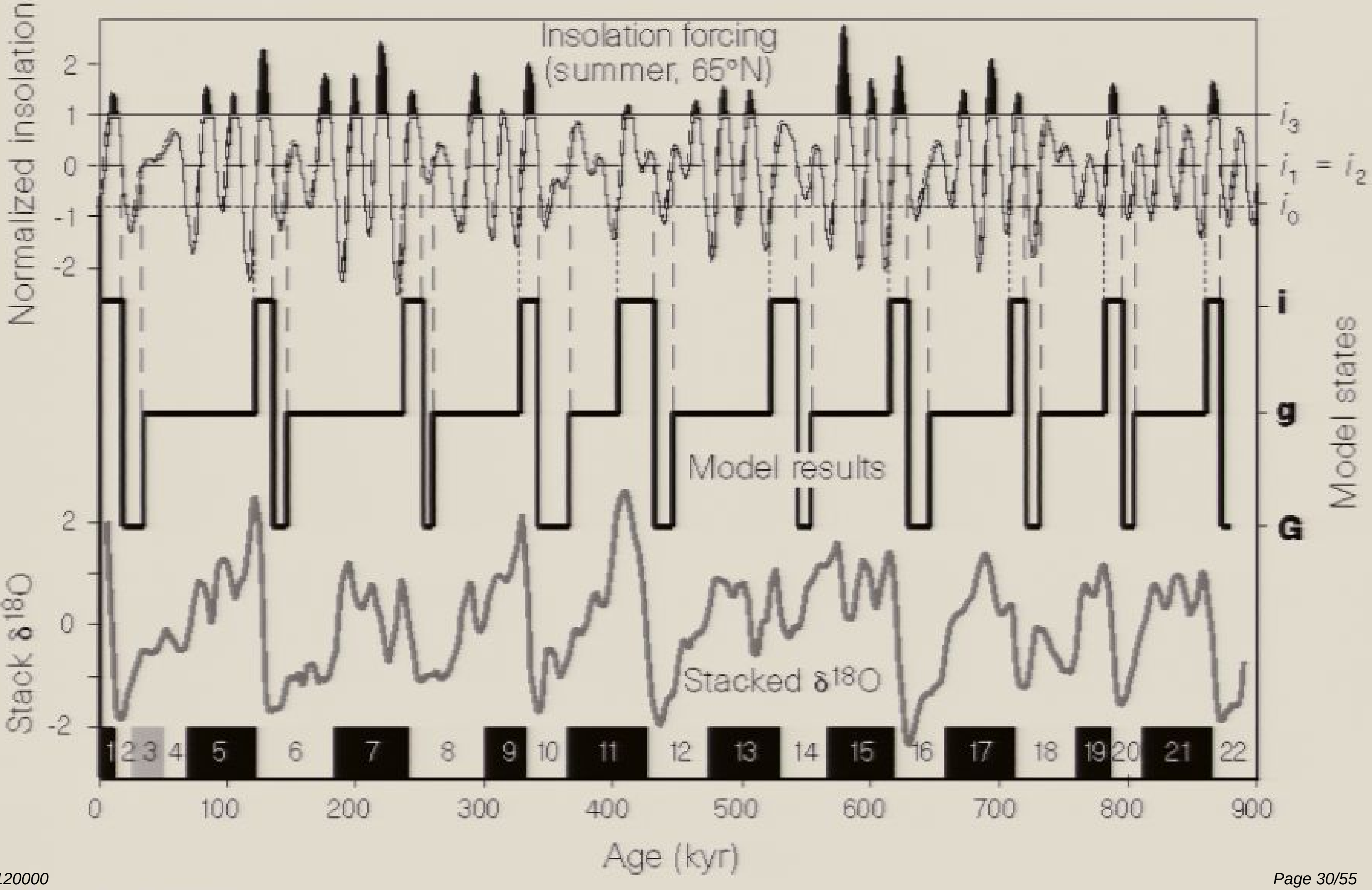
$i > i_{melt}$

Unstable Glacial

$i < i_0$

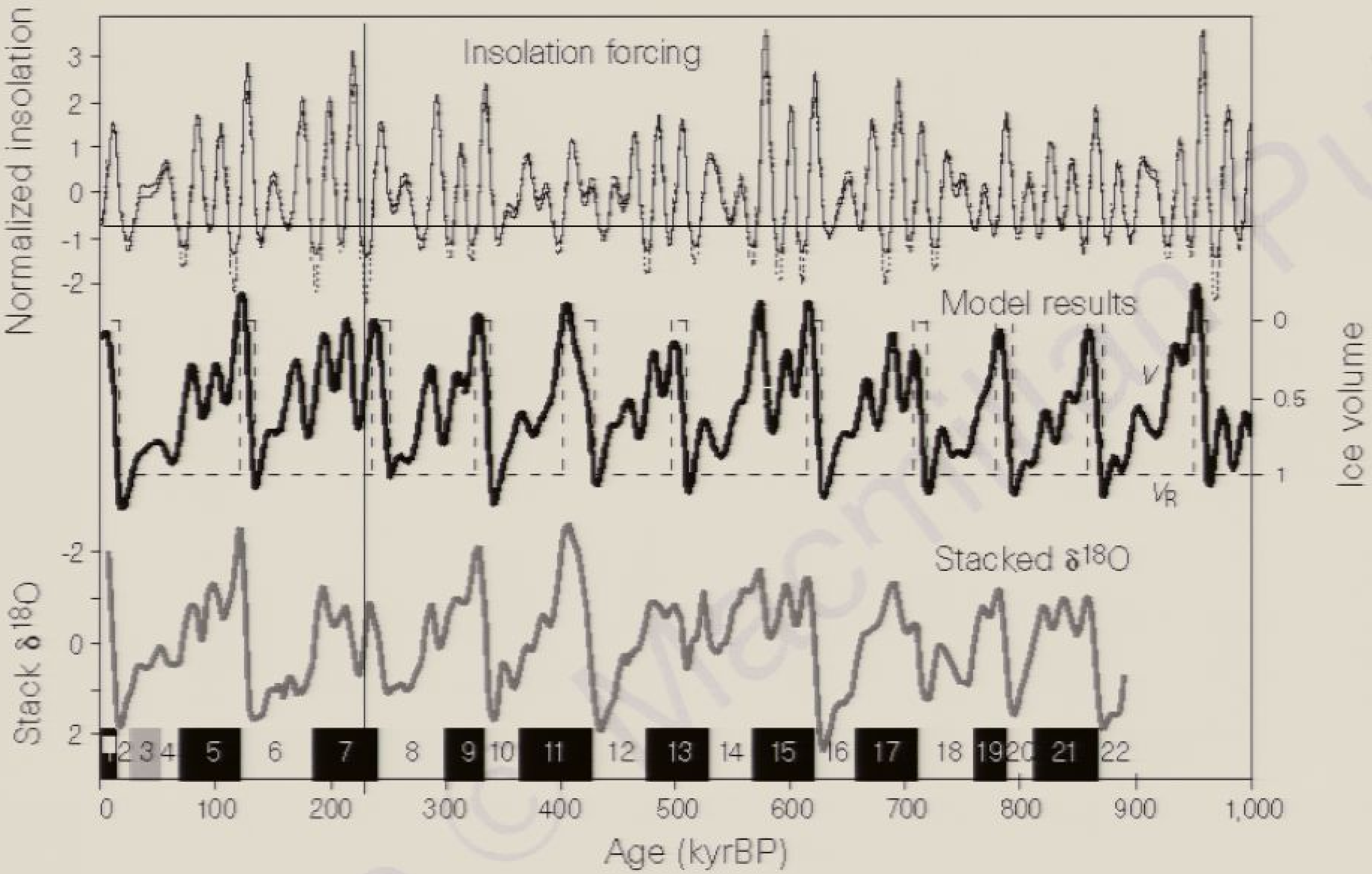
$V > V_{purge}$

Glacial



Paillard, 1998

Gussy it up with ice growth/melting kinetics



Paillard, 1998

Paillard model gets the spectrum better

REVIEWS OF GEOPHYSICS Paillard: GLACIAL C

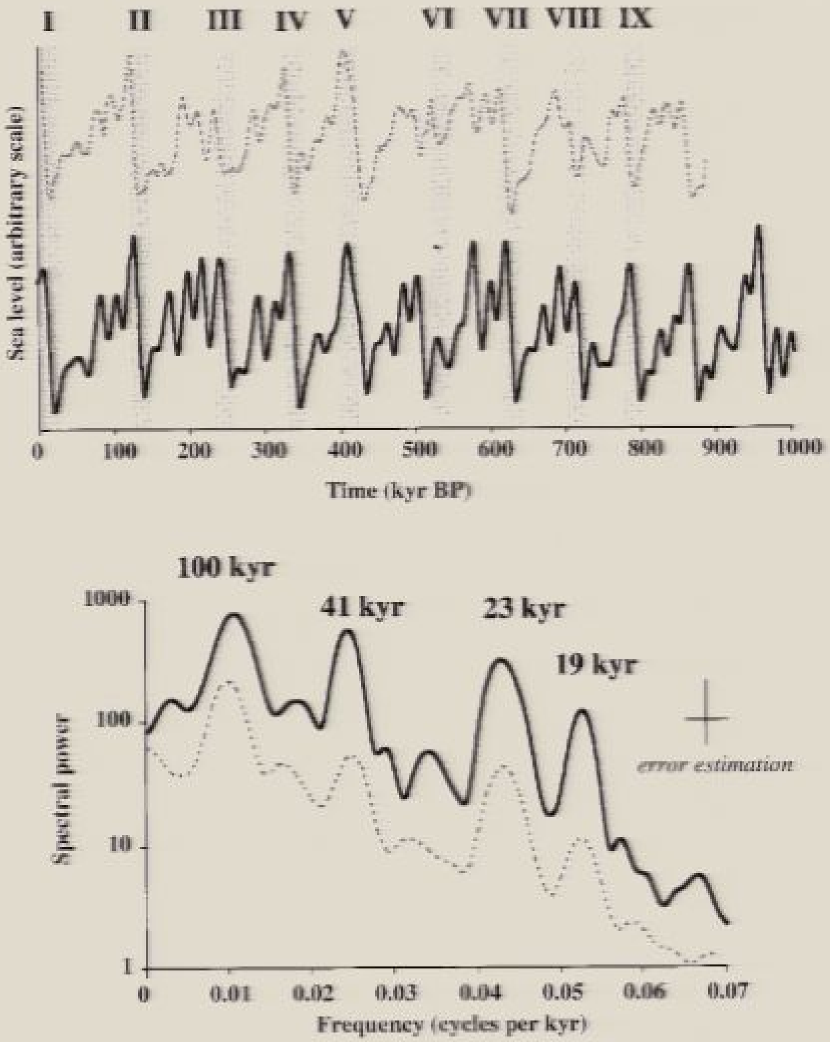
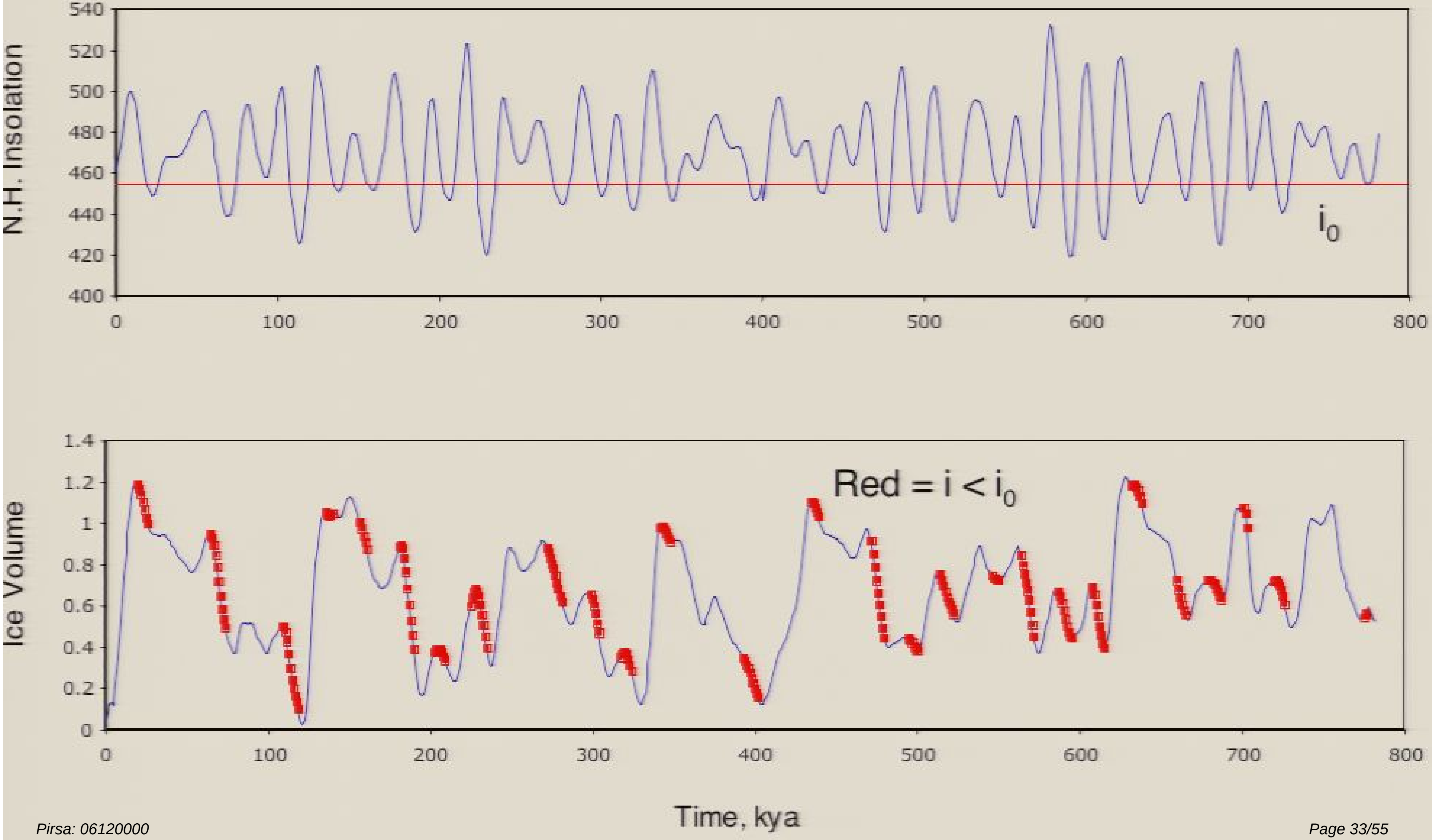


Figure 13. Same as Figure 9, but for *Paillard*'s [1998] model. Threshold values are $i_0 = -0.75$ and $i_1 = 0$. Time constants are $\tau_i = 10$ kyr, $\tau_G = \tau_g = 50$ kyr, and $\tau_F = 25$ kyr.

According to Paillard, 2001

Ice volume responds to N.H. insolation



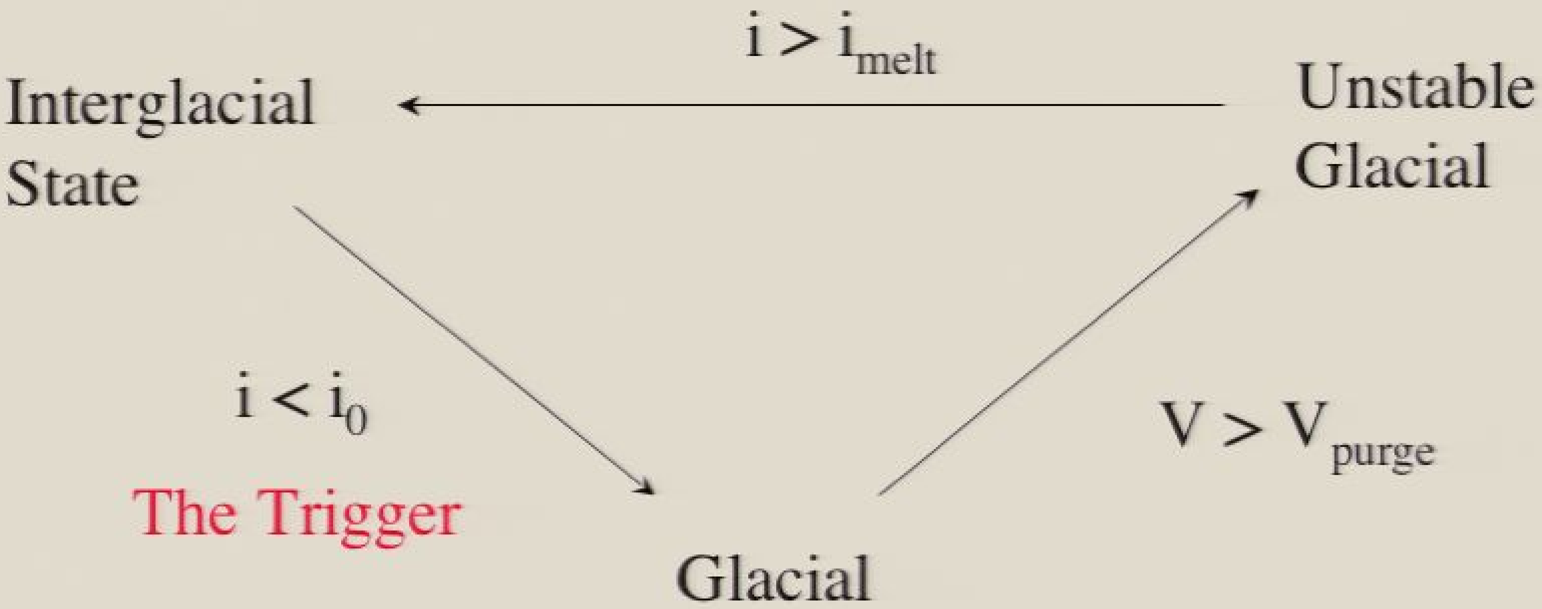
The World According to Paillard

100 kyr cycle arises from the one-way street of the ice sheet life cycle.

Ice definitely responds to $i < i_0$ cold bursts.

The definite link with nucleation is not as clear. The $\delta^{18}O$ impact is similar whether in warm climate or cold.

Paillard model



Interglacial State

$i > i_{melt}$

Unstable Glacial

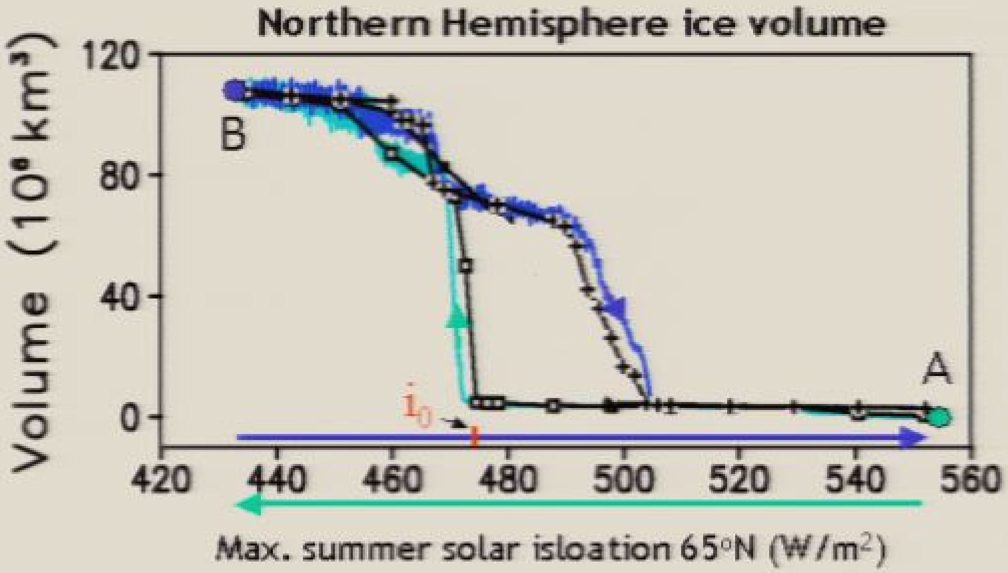
$i < i_0$

The Trigger

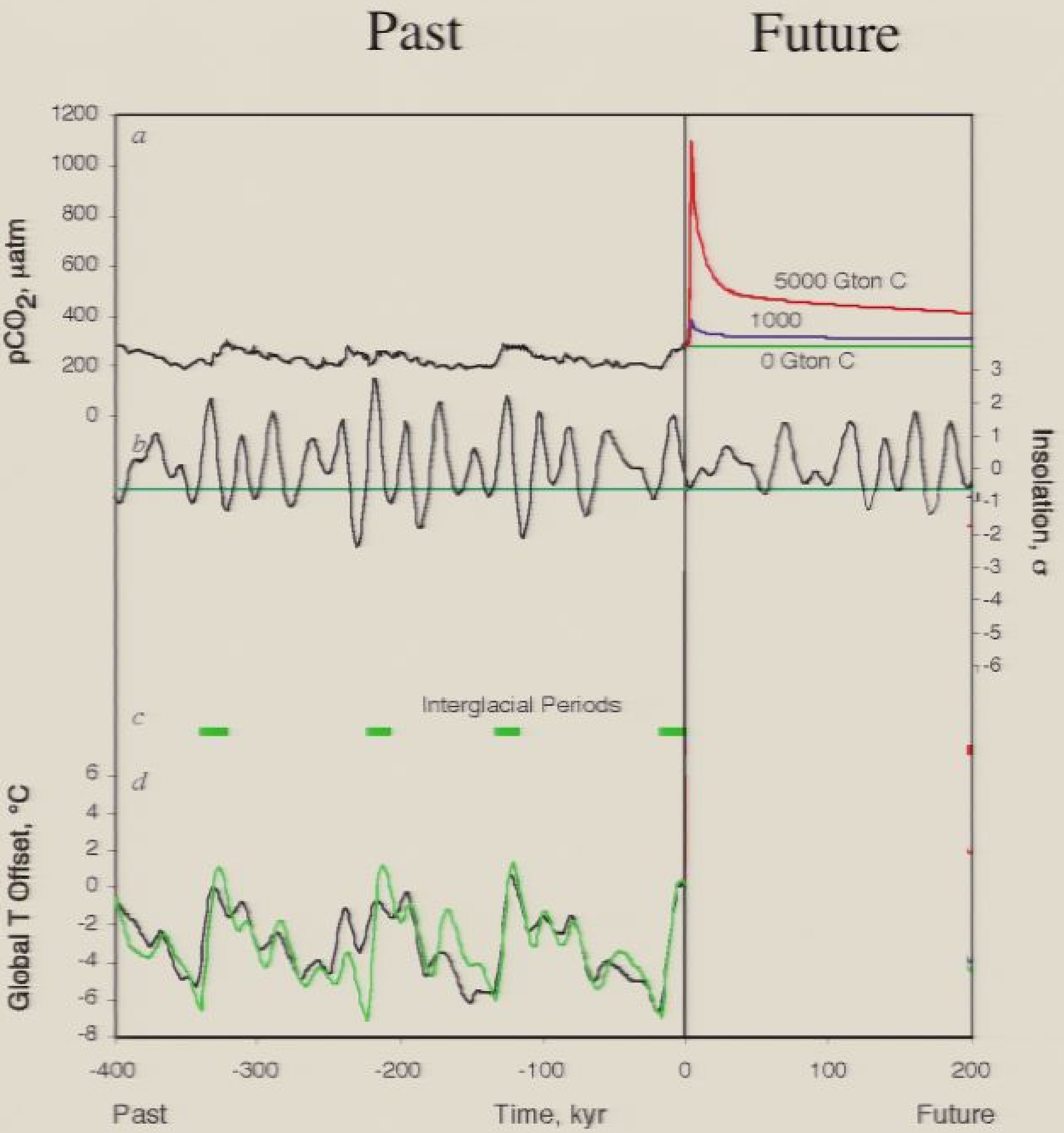
Glacial

$V > V_{purge}$

CLIMBER Model Hysteresis

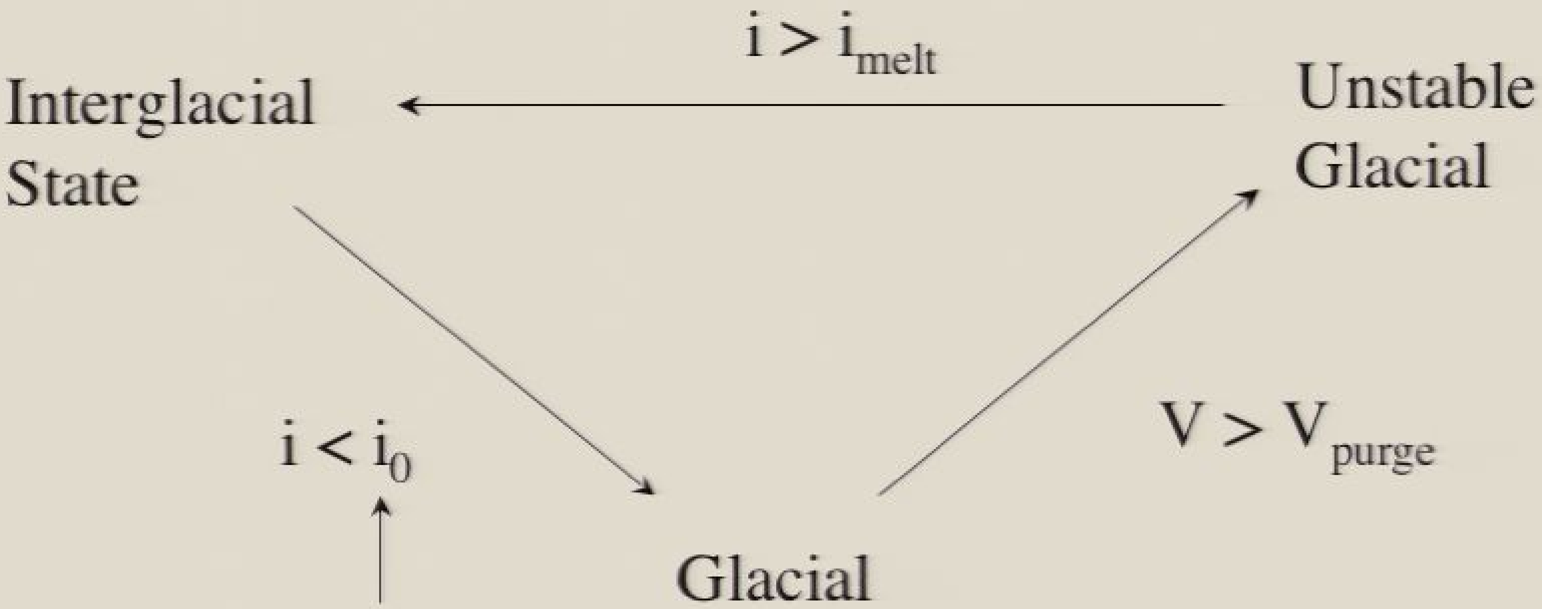


Interglacial mode until sunlight gets too dim.
Then suddenly an ice sheet forms, and it stays there
until sunlight gets even brighter than the original trigger.



Archer and Ganopolski, 2005

Paillard model



$i > i_{melt}$

Interglacial State

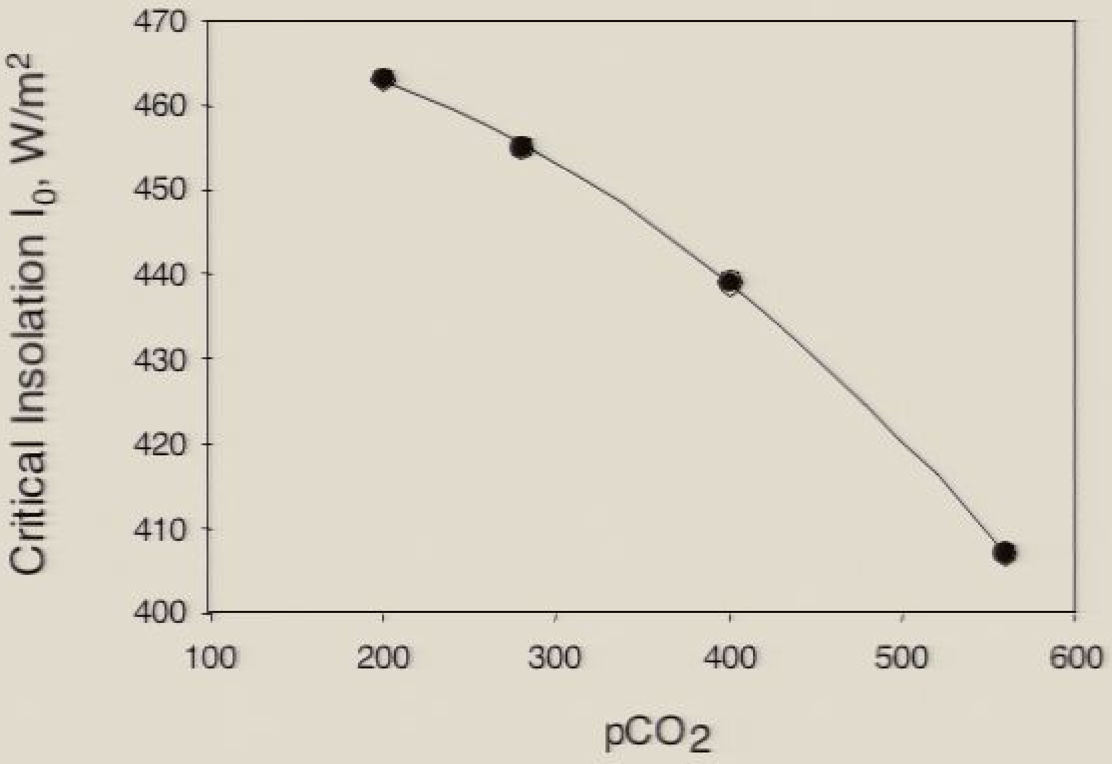
Unstable Glacial

$i < i_0$

Glacial

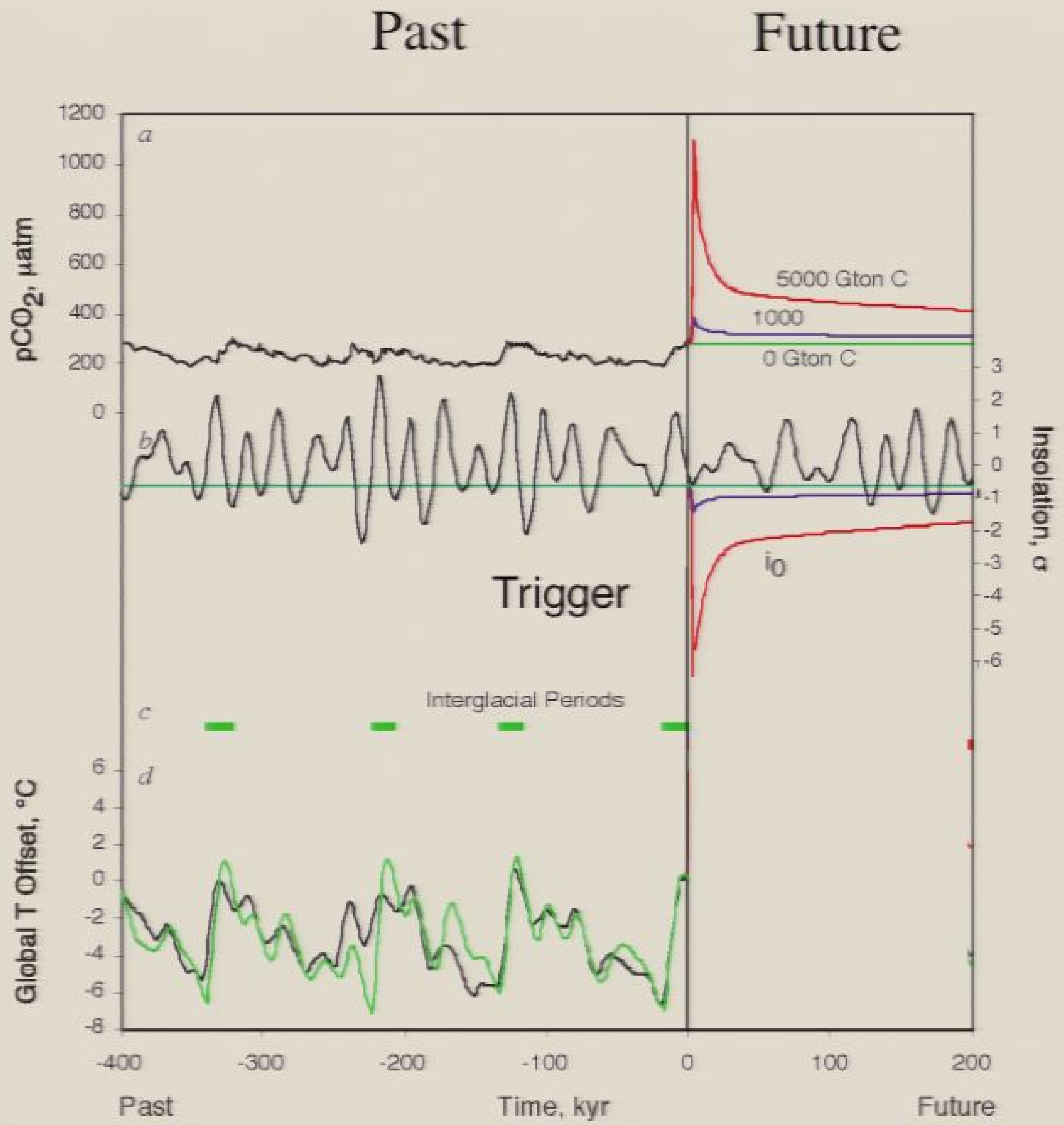
$V > V_{purge}$

Baseline pCO_2 changes i_0, moving the trigger



If CO_2 is higher,
it takes a stronger
sunlight change
to trigger formation
of an ice sheet.

Archer and Ganopolski, 2005

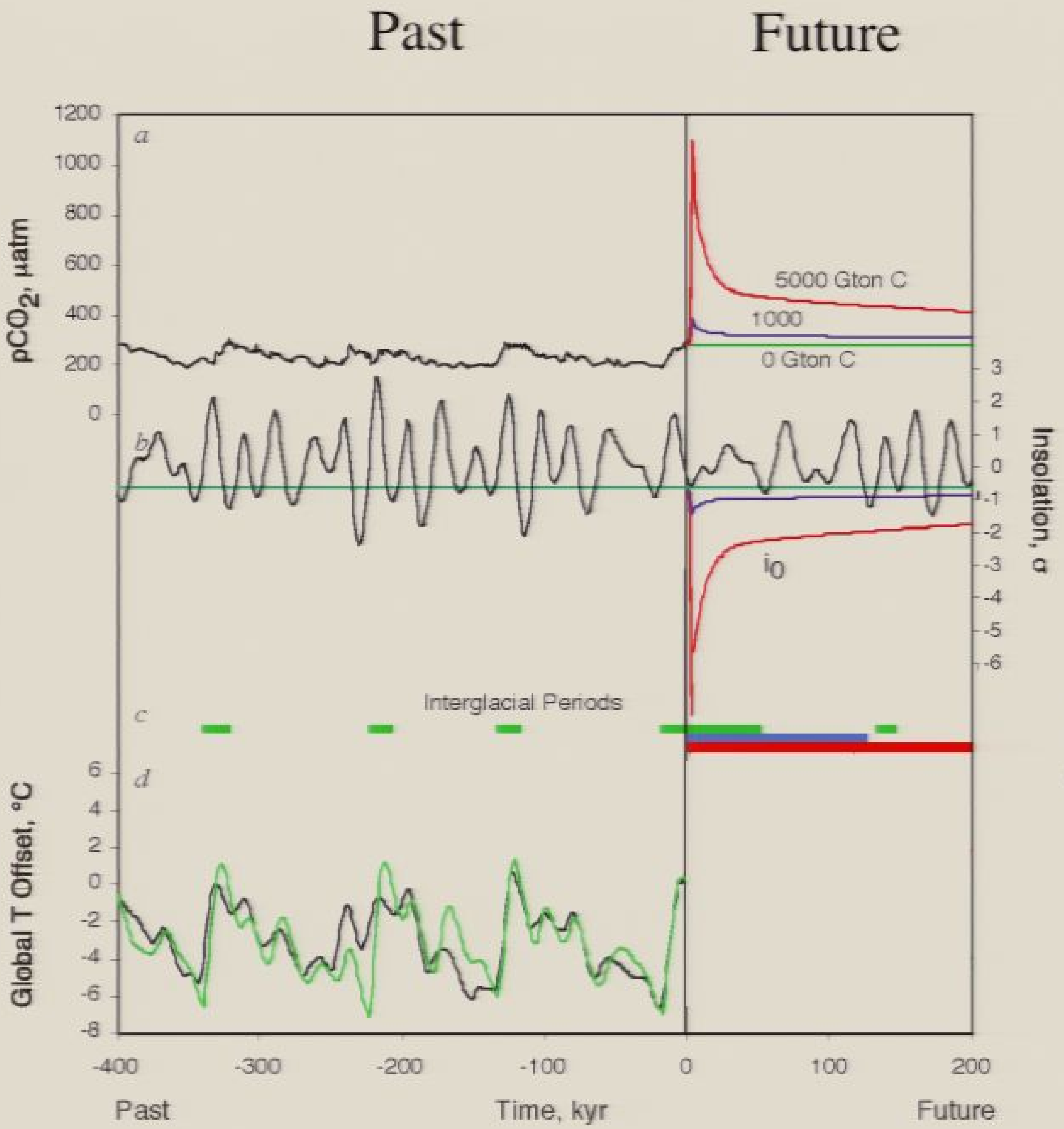


Archer and Ganopolski, 2005

A Crude Temperature Estimate

$$\Delta T_{\mathrm{total}} = 6^\circ\mathrm{C} \cdot \underset{\uparrow}{\Delta \mathrm{ice}} + 3^\circ\mathrm{C} \cdot \frac{\ln[(p\mathrm{CO}_2 - 278)/278]}{\ln(2)}$$

Includes the glacial/interglacial $p\mathrm{CO}_2$ feedback.



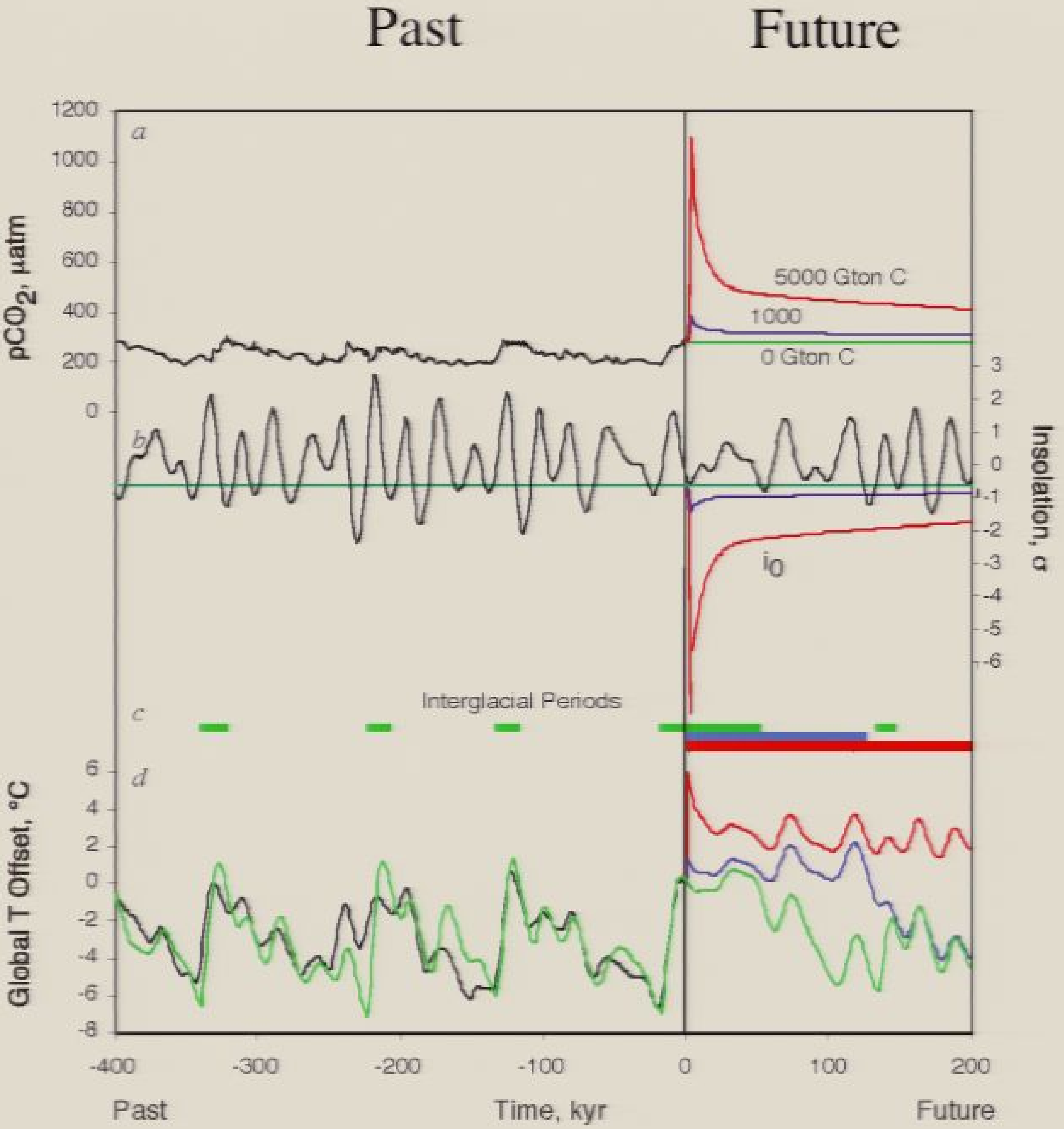
No Ice Age
for 500 Millennia

Archer and Ganopolski, 2005

A Crude Temperature Estimate

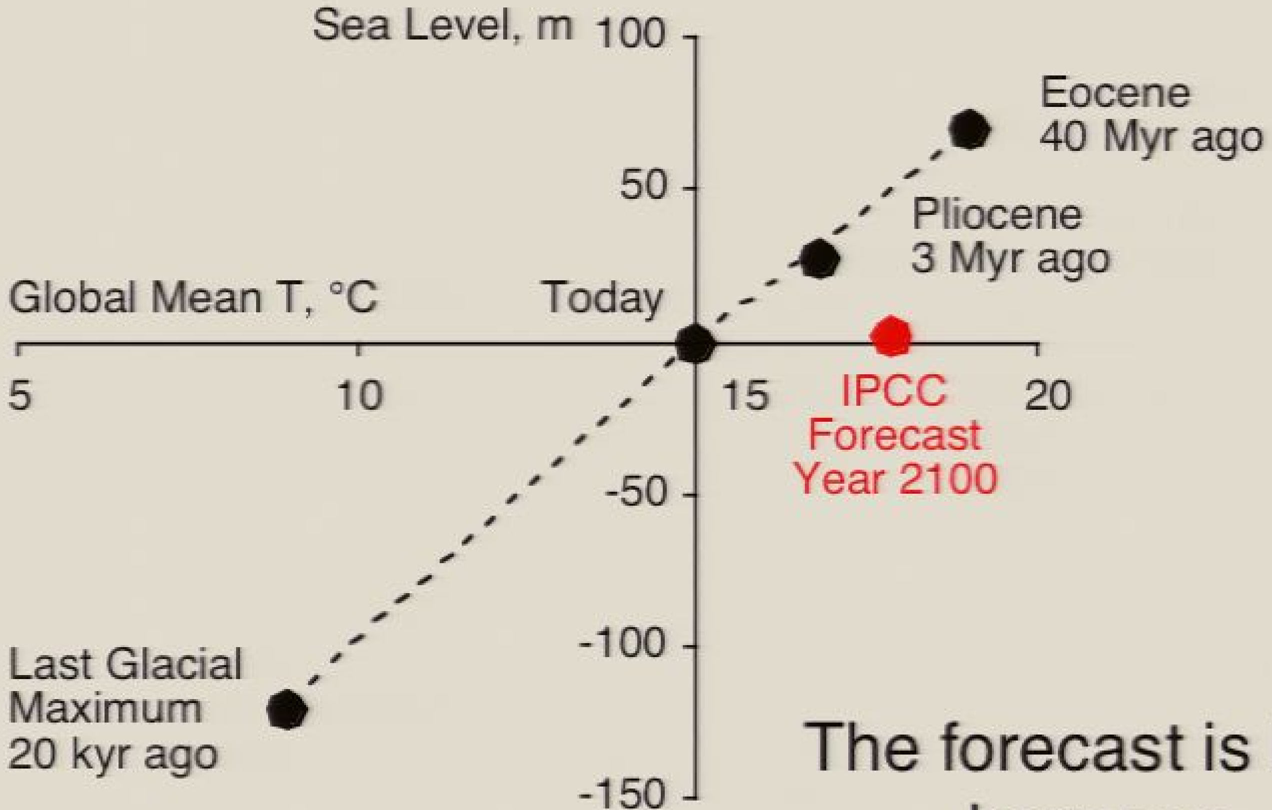
$$\Delta T_{\text{total}} = 6^\circ\text{C} \cdot \Delta \text{ice} + 3^\circ\text{C} \cdot \frac{\ln[(pCO_2 - 278)/278]}{\ln(2)}$$

Includes the glacial/interglacial pCO_2 feedback.



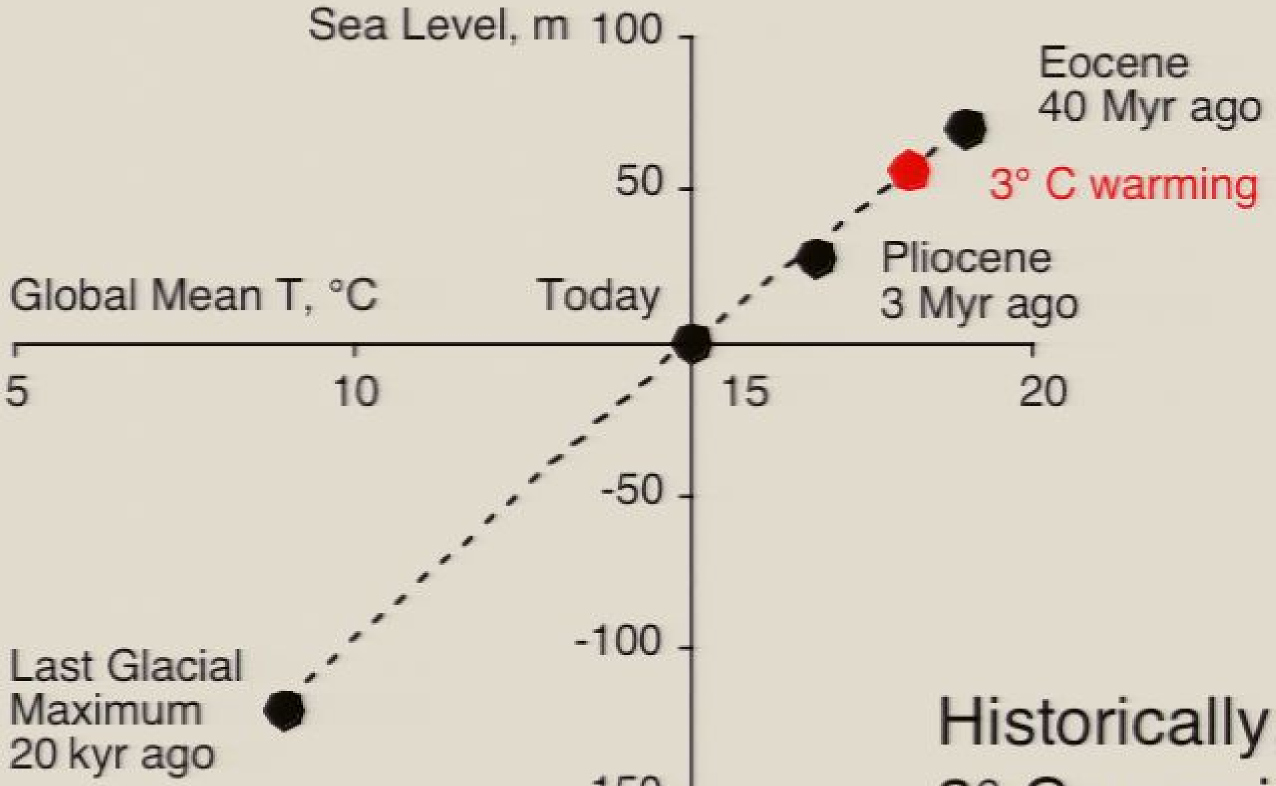
Archer and Ganopolski, 2005

Sea Level



The forecast is low
because
melting ice is slow

Sea Level

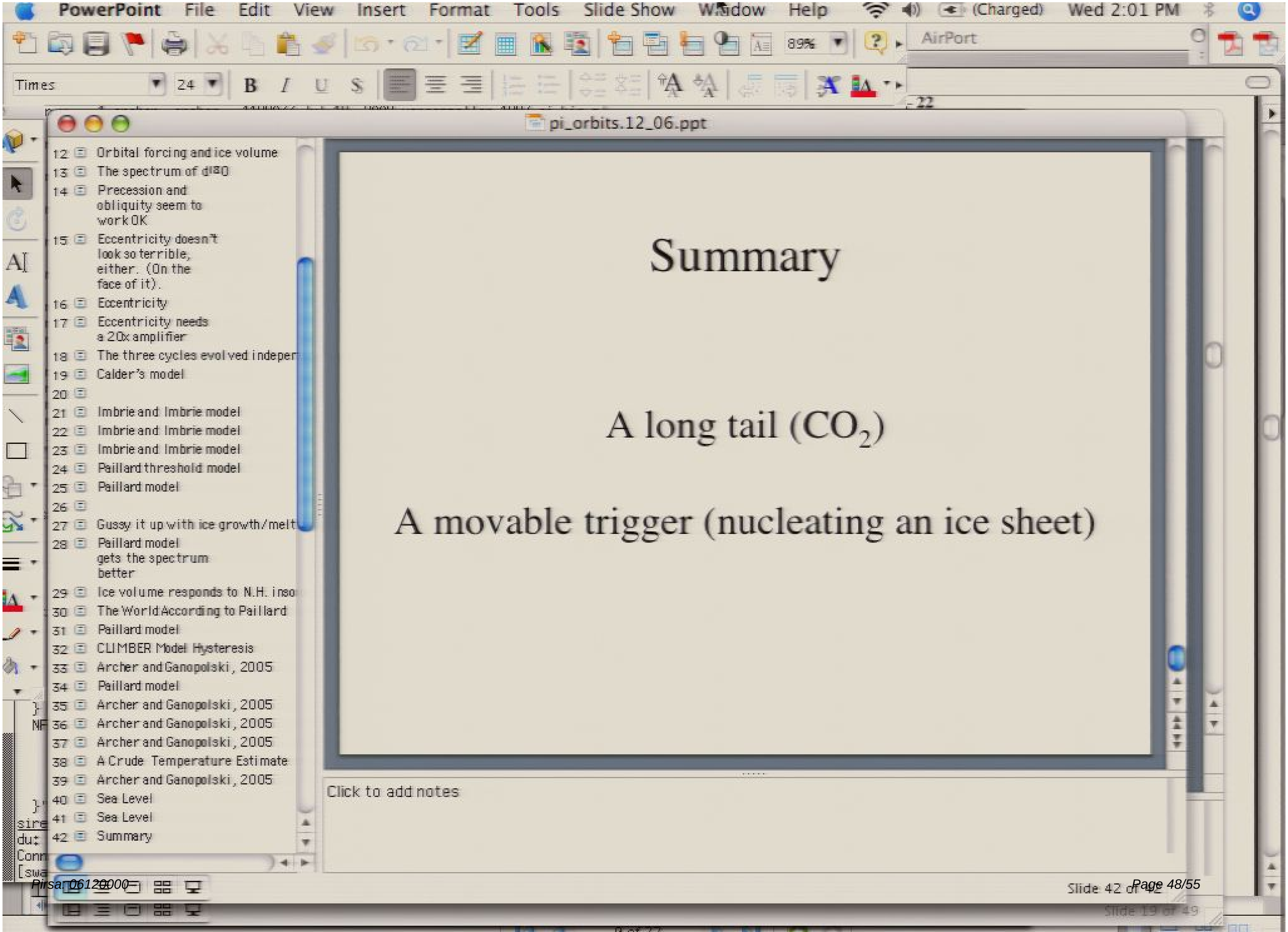


Historically,
3° C warming
is a big deal.

Summary

A long tail (CO_2)

A movable trigger (nucleating an ice sheet)



12 Orbital forcing and ice volume
13 The spectrum of d18O
14 Precession and obliquity seem to work OK
15 Eccentricity doesn't look so terrible, either. (On the face of it).
16 Eccentricity
17 Eccentricity needs a 20x amplifier
18 The three cycles evolved indeper
19 Calder's model
20
21 Imbrie and Imbrie model
22 Imbrie and Imbrie model
23 Imbrie and Imbrie model
24 Paillard threshold model
25 Paillard model
26
27 Gussy it up with ice growth/melt
28 Paillard model gets the spectrum better
29 Ice volume responds to N.H. inso
30 The World According to Paillard
31 Paillard model
32 CLIMBER Model Hysteresis
33 Archer and Ganopolski, 2005
34 Paillard model
35 Archer and Ganopolski, 2005
36 Archer and Ganopolski, 2005
37 Archer and Ganopolski, 2005
38 A Crude Temperature Estimate
39 Archer and Ganopolski, 2005
40 Sea Level
41 Sea Level
42 Summary

Summary

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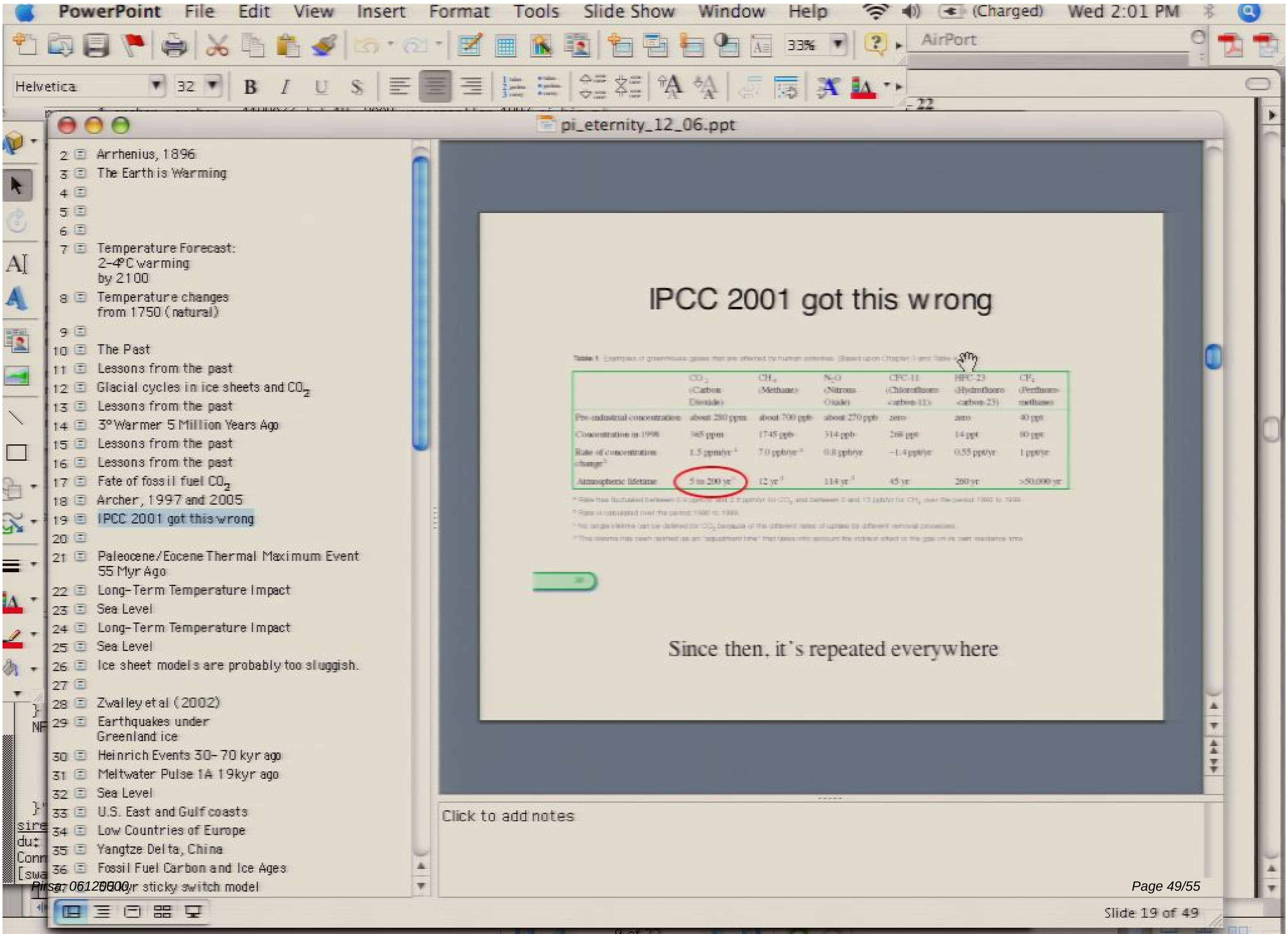

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32 Sea Level
33 U.S. East and Gulf coasts
34 Low Countries of Europe
35 Yangtze Delta, China
36 Fossil Fuel Carbon and Ice Ages
yr sticky switch model

IPCC 2001 got this wrong

	CO_2 (Carbon Dioxide)	CH_4 (Methane)	N_2O (Nitrous Oxide)	CFC-11 (Chlorofluoro-carbon-11)	HFC-23 (Hydrofluoro-carbon-23)	CF_4 (Perfluoro-methane)
Pre-industrial concentration	about 280 ppm	about 700 ppb	about 270 ppb	zero	zero	40 ppt
Concentration in 1998	365 ppm	1745 ppb	314 ppb	268 ppt	14 ppt	80 ppt
Rate of concentration change [b]	1.5 ppm/yr [a]	7.0 ppb/yr [a]	0.8 ppb/yr	−1.4 ppt/yr	0.55 ppt/yr	1 ppt/yr
Atmospheric lifetime	5 to 200 yr [c]	12 yr [d]	114 yr [d]	45 yr	260 yr	>50,000 yr

Since then, it's repeated everywhere

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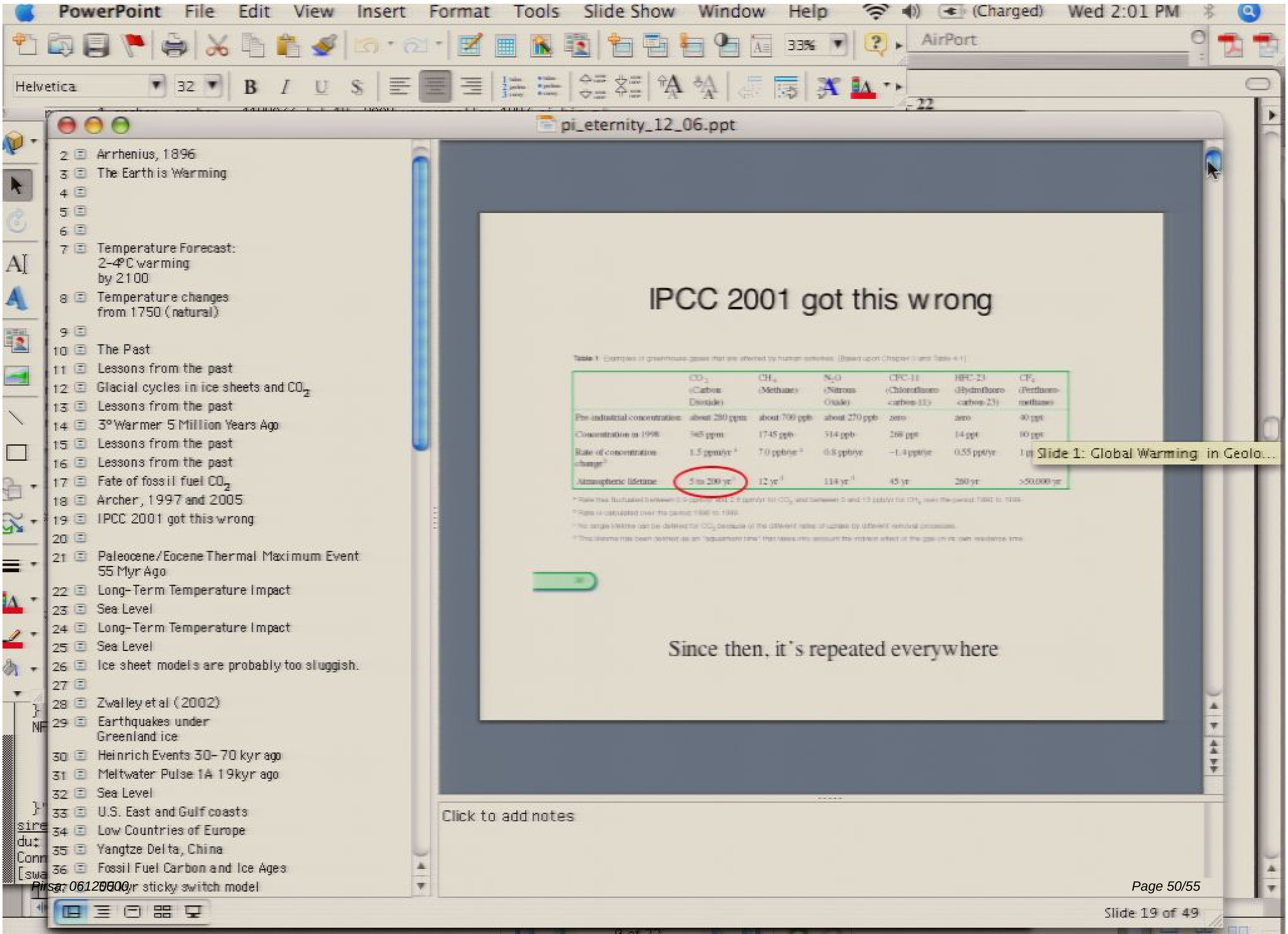

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Since then, it's repeated everywhere

Slide 1: Global Warming in Geolo...

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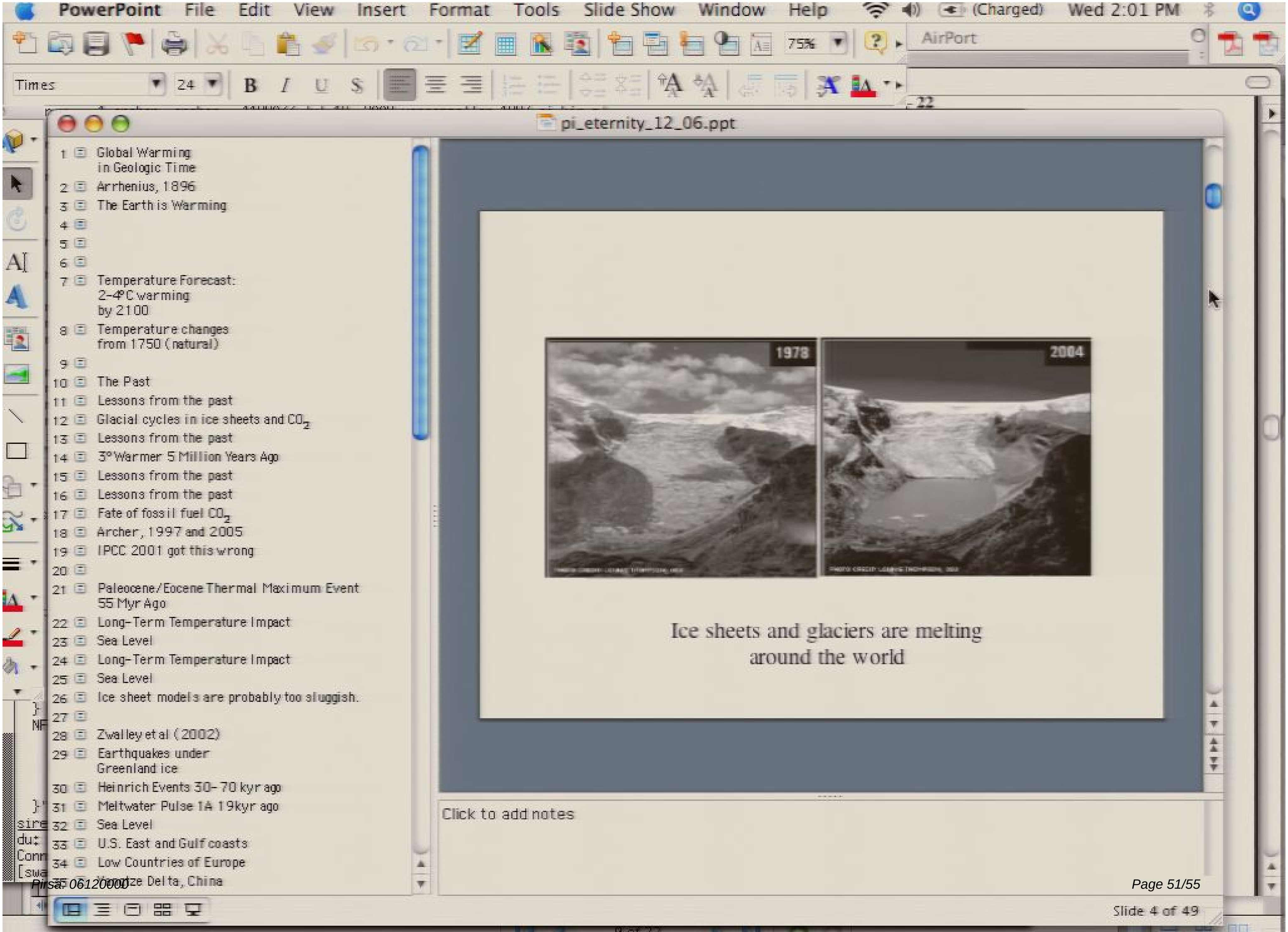

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Ice sheets and glaciers are melting around the world

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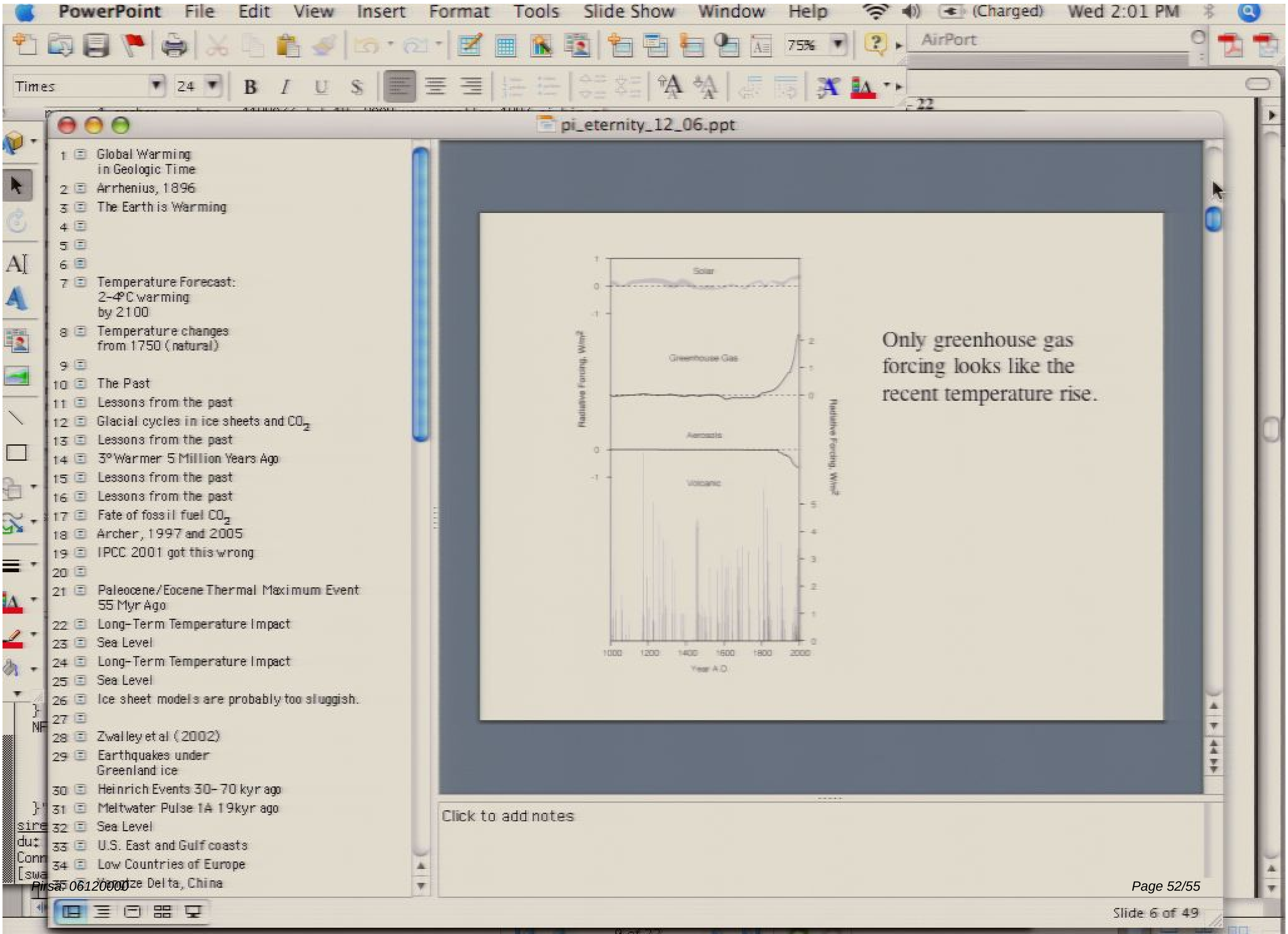

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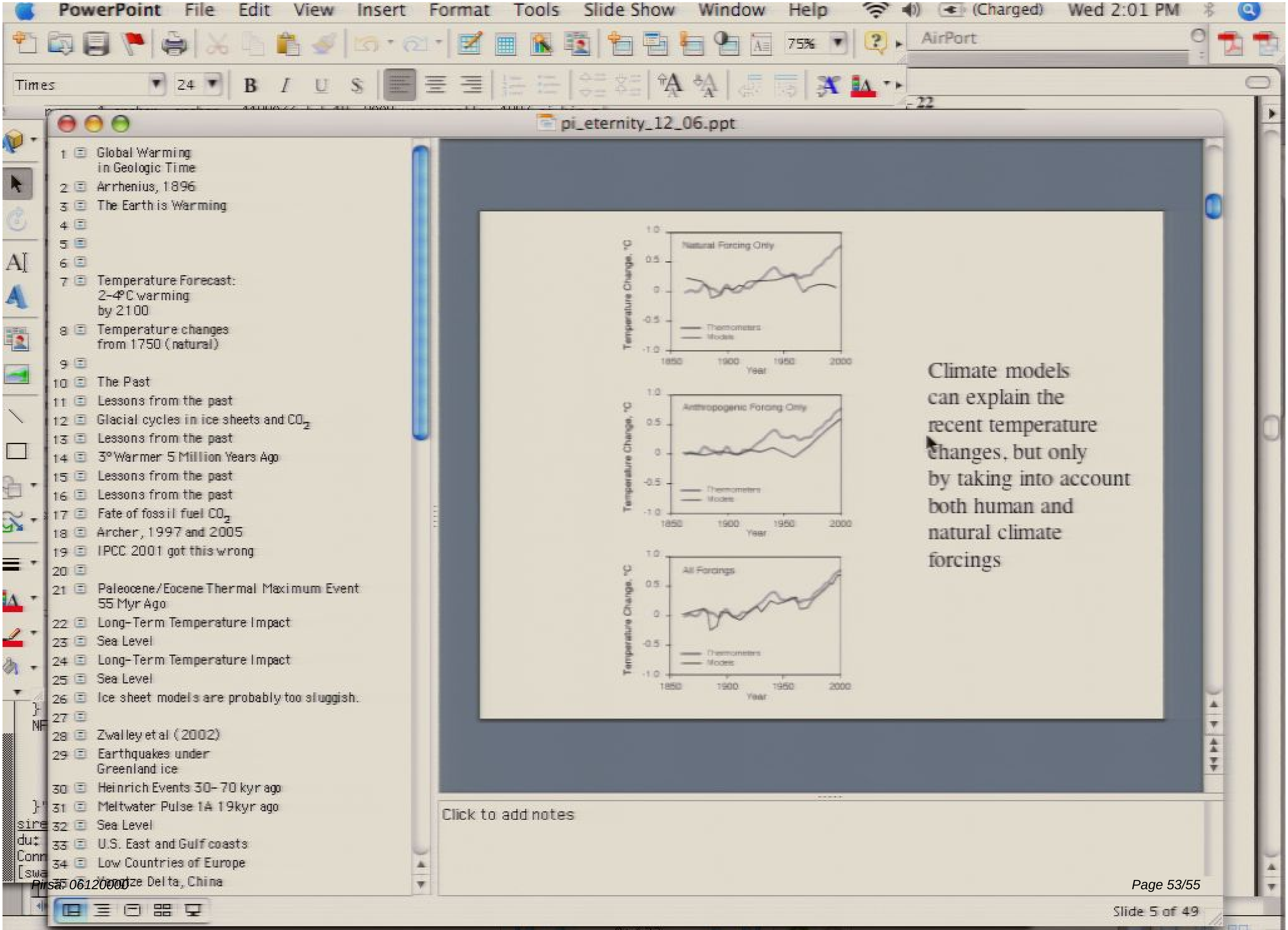
Only greenhouse gas forcing looks like the recent temperature rise.



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Climate models can explain the recent temperature changes, but only by taking into account both human and natural climate forcings

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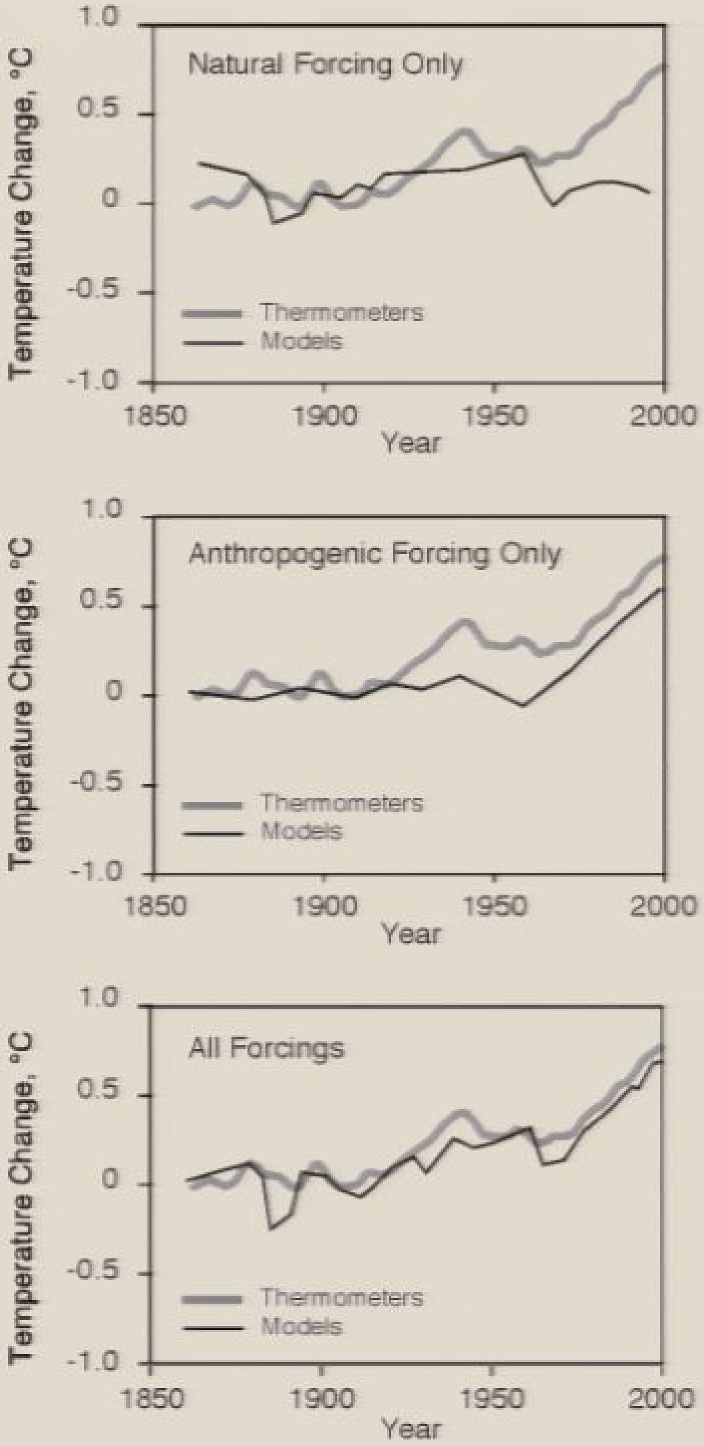

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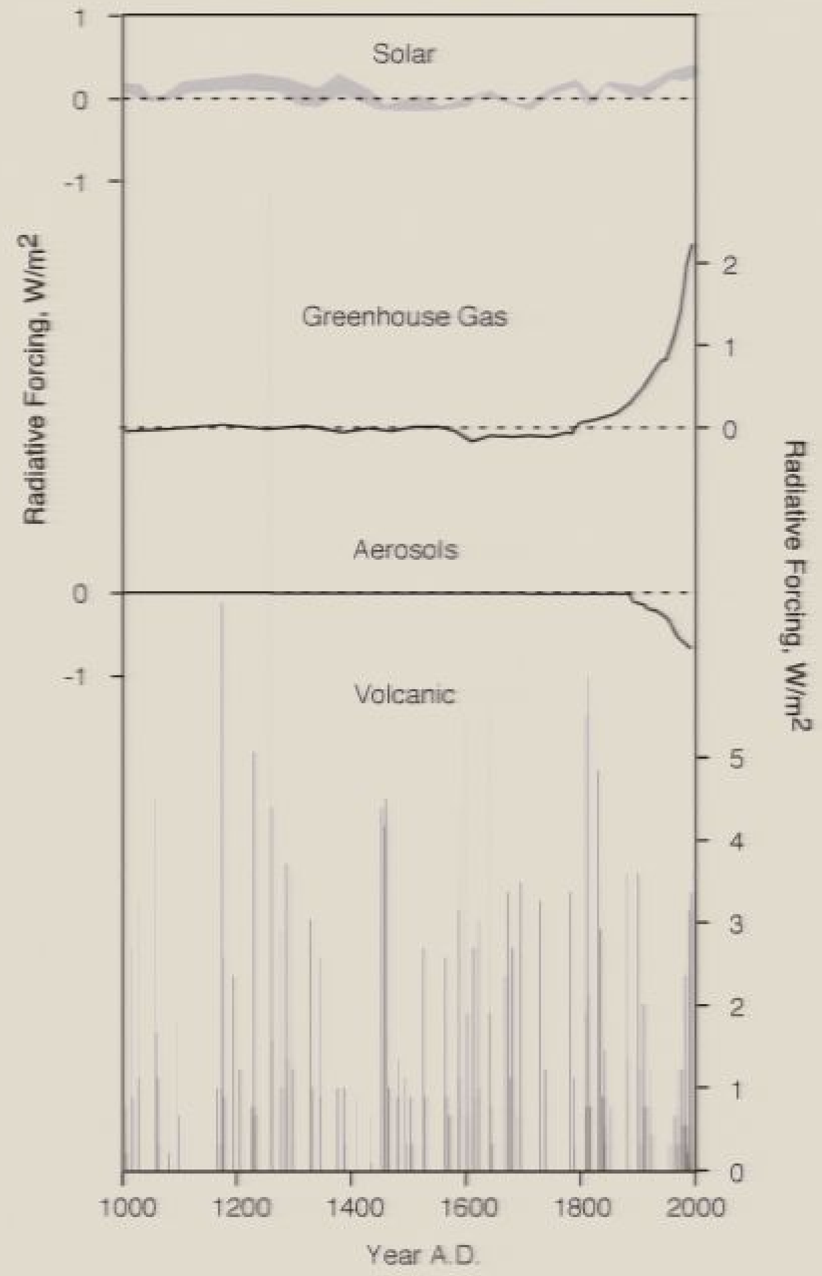

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