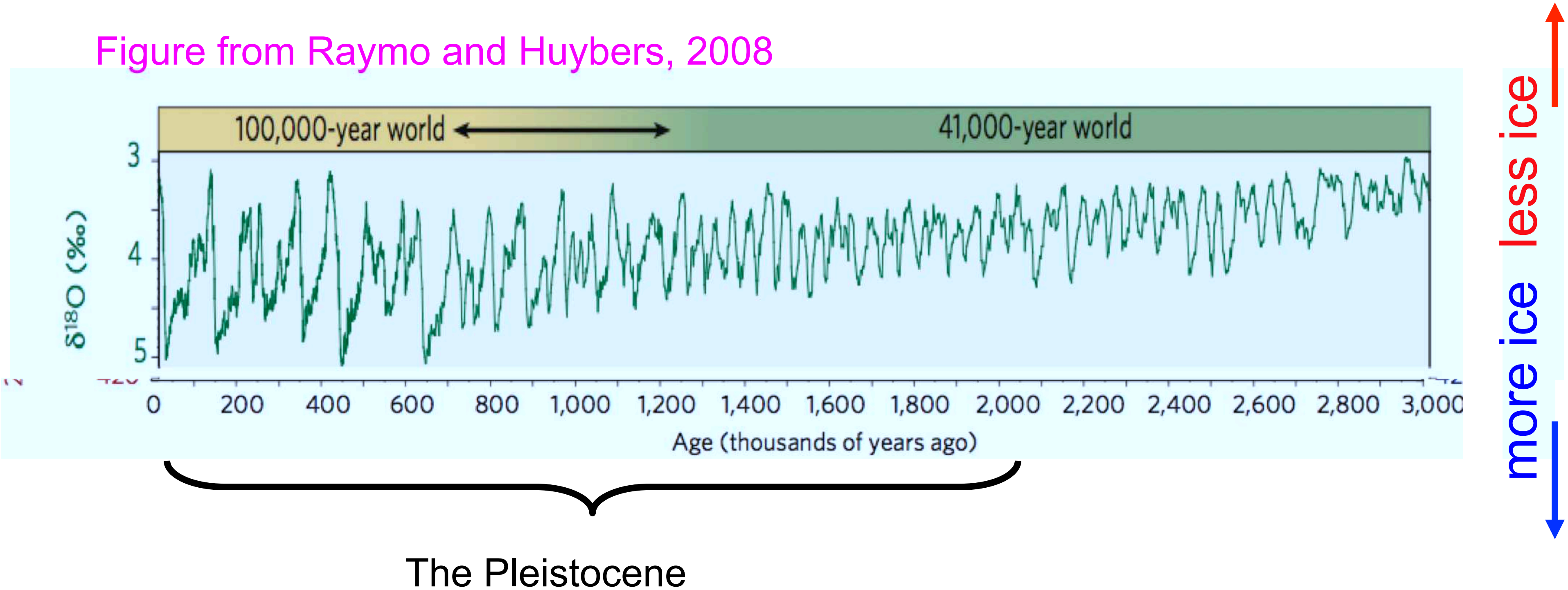
A brief lesson on oxygen isotopes

Figure from Raymo and Huybers, 2008

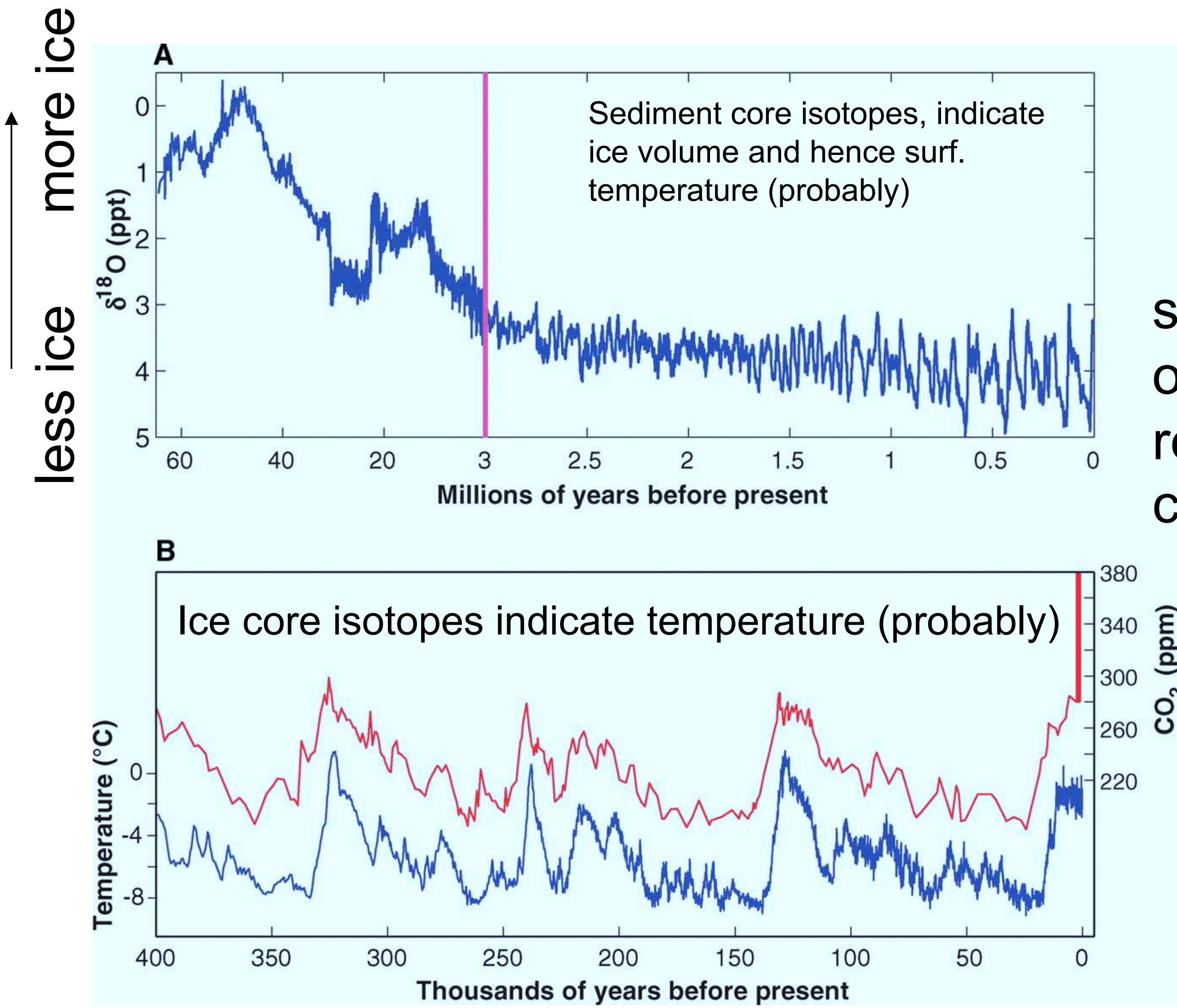


(1) $\delta^{18}O$ in sediments is directly related to ice volume. Because ice sheets deplete the supply of $^{16}O_2$ from seawater

(2) Also $\delta^{18}O$ is inversely related to temperature. Because plankton take up higher rates of $^{18}O_2$ when it is colder.

(Fortunately 1 & 2 work together)

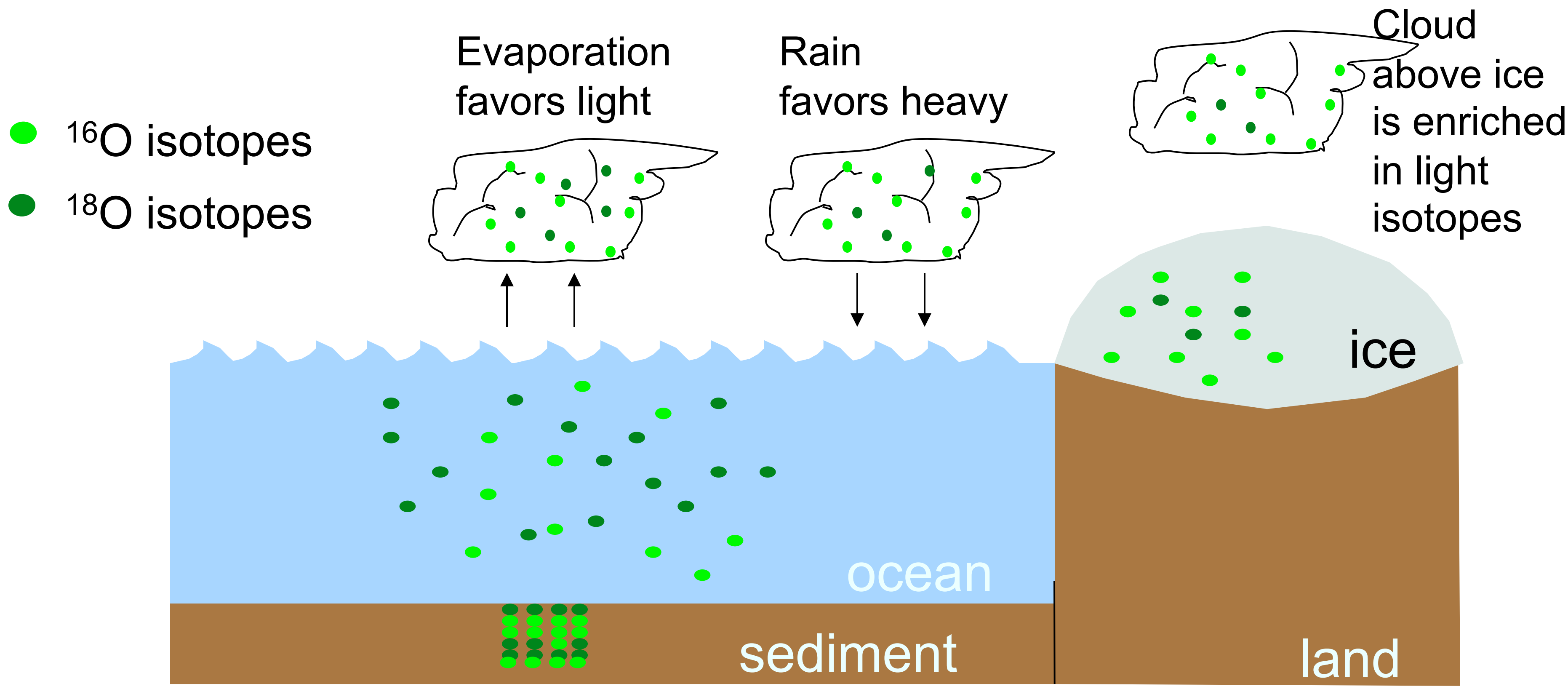
There are different kinds of isotope records!



sediment cores offer much longer records than ice cores

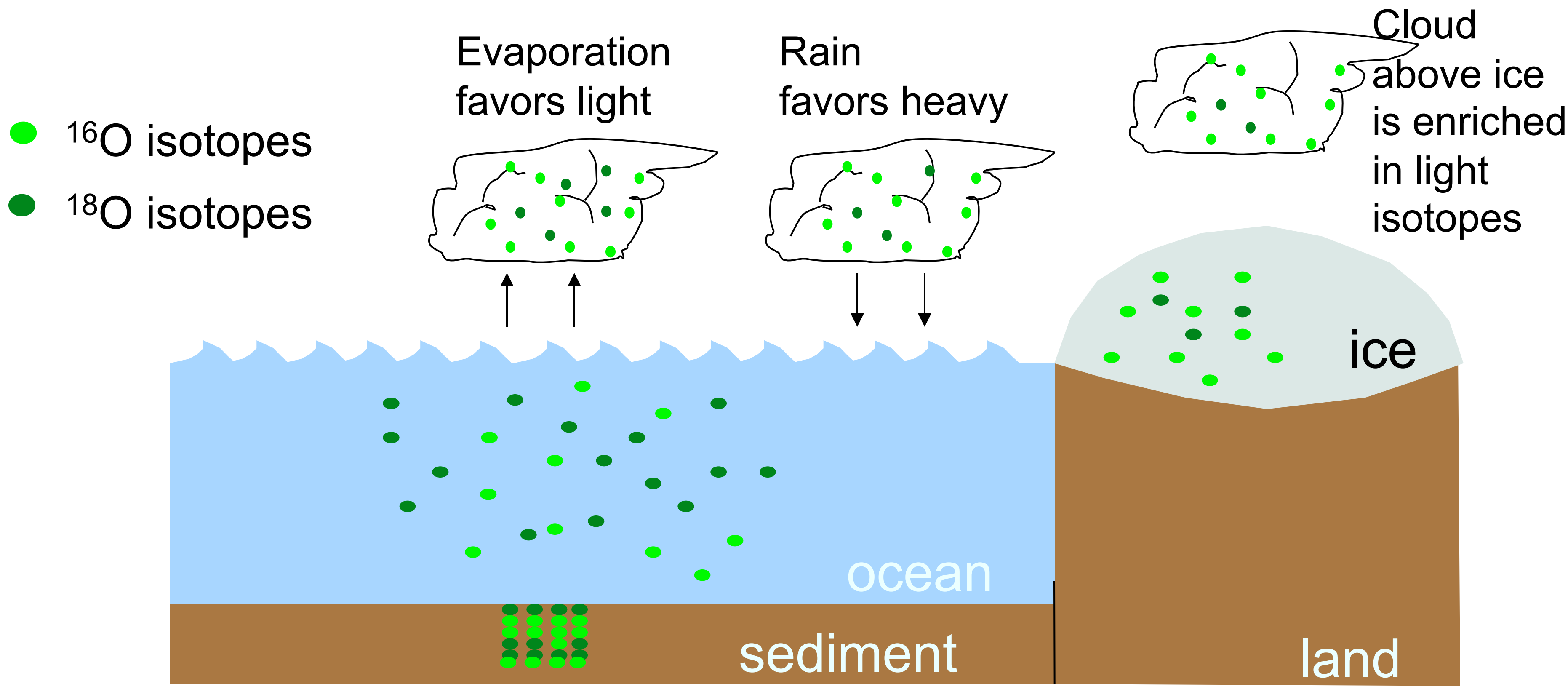
Fedora et al 2006

δ^{18}O from ocean sediments as proxy for ice volume

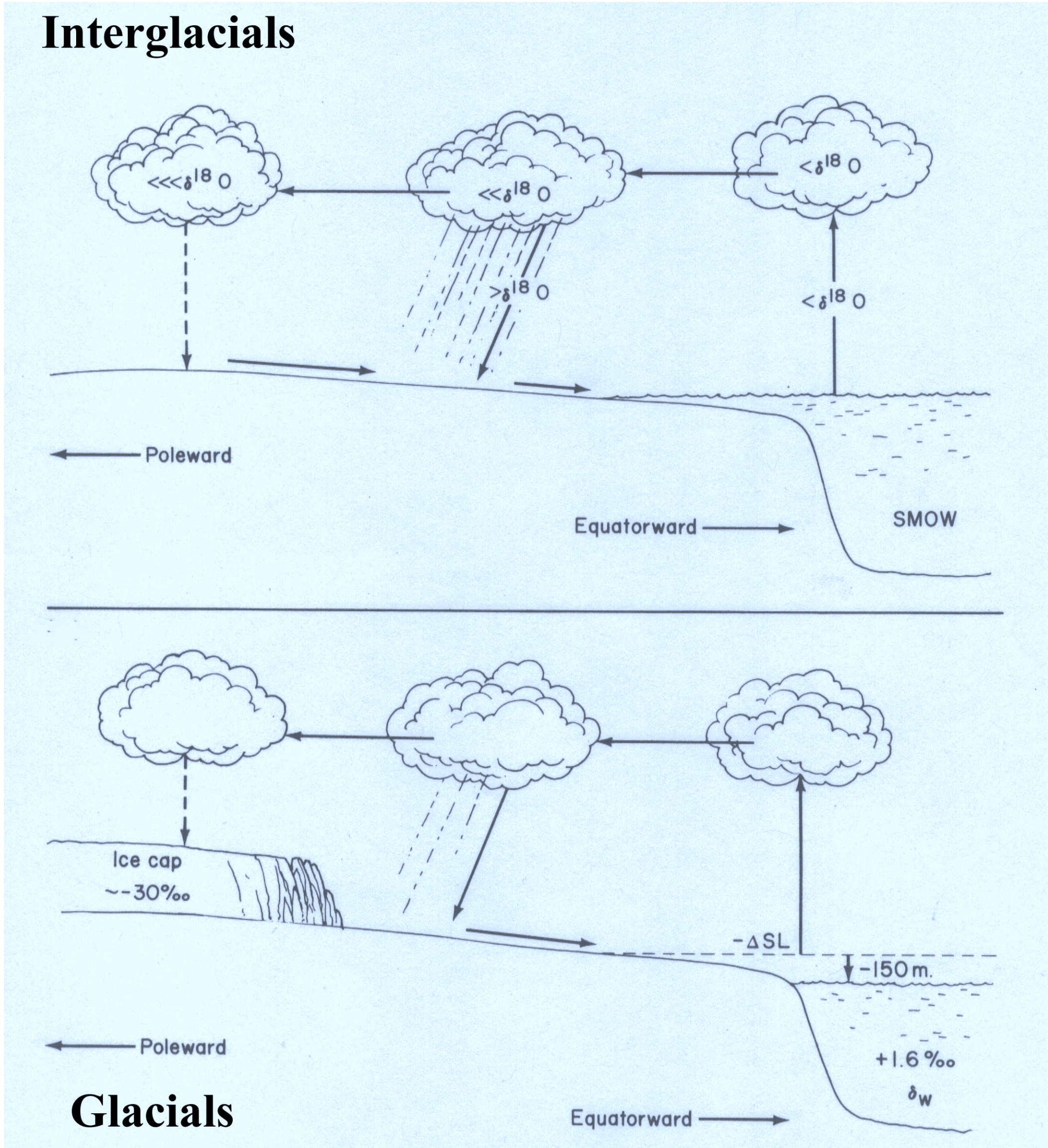


- Fractionation of isotopes during evaporation and precipitation favors light isotopes being transported to ice sheets
- Sediments become rich in heavy isotopes when ice sheets are large because ice sheets preferentially store light isotopes

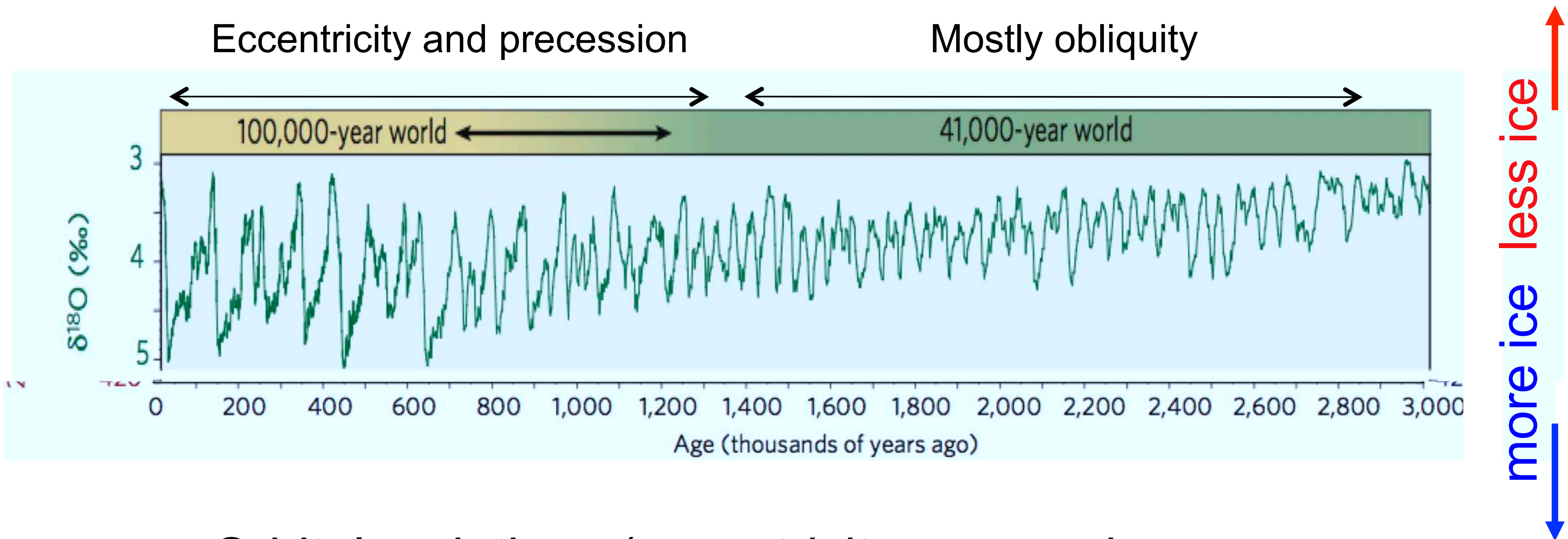
$\delta^{18}O$ from ocean sediments as proxy for ice volume



$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) * 1000\ ^o/_{oo}$$

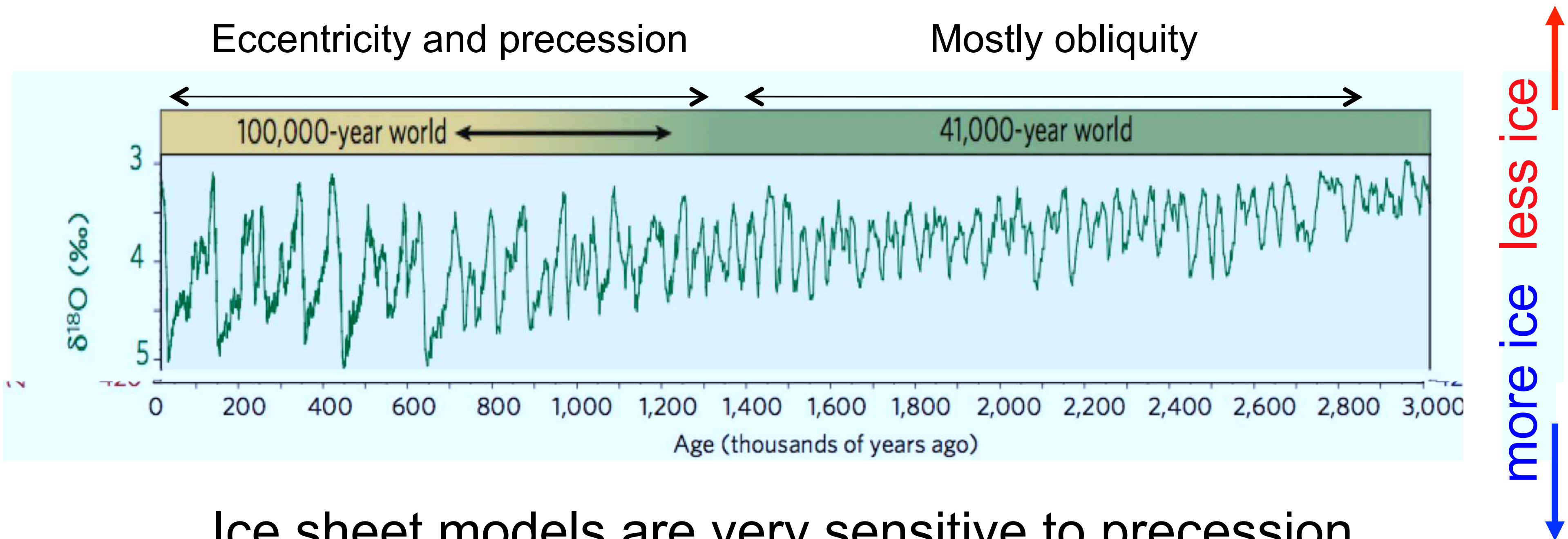


Interglacials
<<<δ18 O
<<δ18 O
<δ18 O
>δ18 O
<δ18 O
Poleward
Equatorward
SMOW
Ice cap
~-30‰
-ΔSL
-150 m.
+1.6 ‰
δw
Poleward
Glacials
Equatorward



Orbital variations (eccentricity, precession, obliquity) of Earth cause solar radiation at a given location to vary

"Climate scientists still do not understand how subtle shifts in insolation at the top of the atmosphere are converted into massive changes in the ice volume on the ground."
Raymo and Huybers, 2008

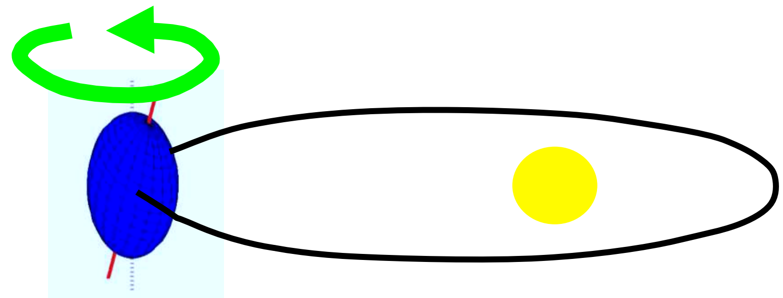


Ice sheet models are very sensitive to precession signal.

Raymo and Huybers ask why isn't there a precession signal in the 41k world?

Are the ice sheet models wrong?
Or are we misinterpreting the δ18O proxy?

- **Precession** (wobble)
  ~19, 23 kyr



Also known as precession of the equinoxes. Summers are coldest when summer season is furthest from sun.

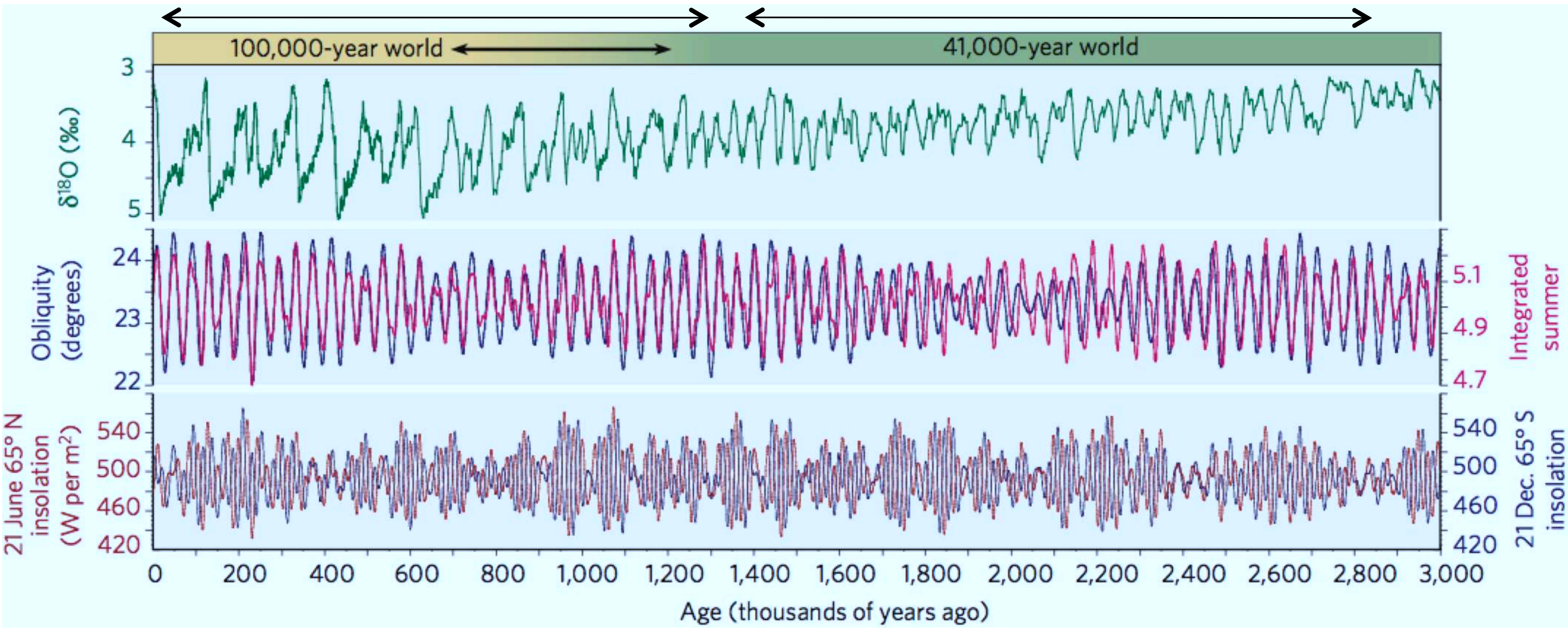
Traditional view has been that ice sheets are sensitive to peak or mean summer insolation.

Huybers (2006) proposed instead that the more important issue is integrated summer insolation (counting only days when insolation exceeded a threshold). Duration and intensity are anticorrelated because of Kepler's law.

Raymo et al (2006) proposed yet another alternative where they argued that because precession has opposite effects in the two hemispheres, the sediments, which provide a proxy of both hemispheres at once, cannot measure hemispheric asymmetries.

Eccentricity and precession

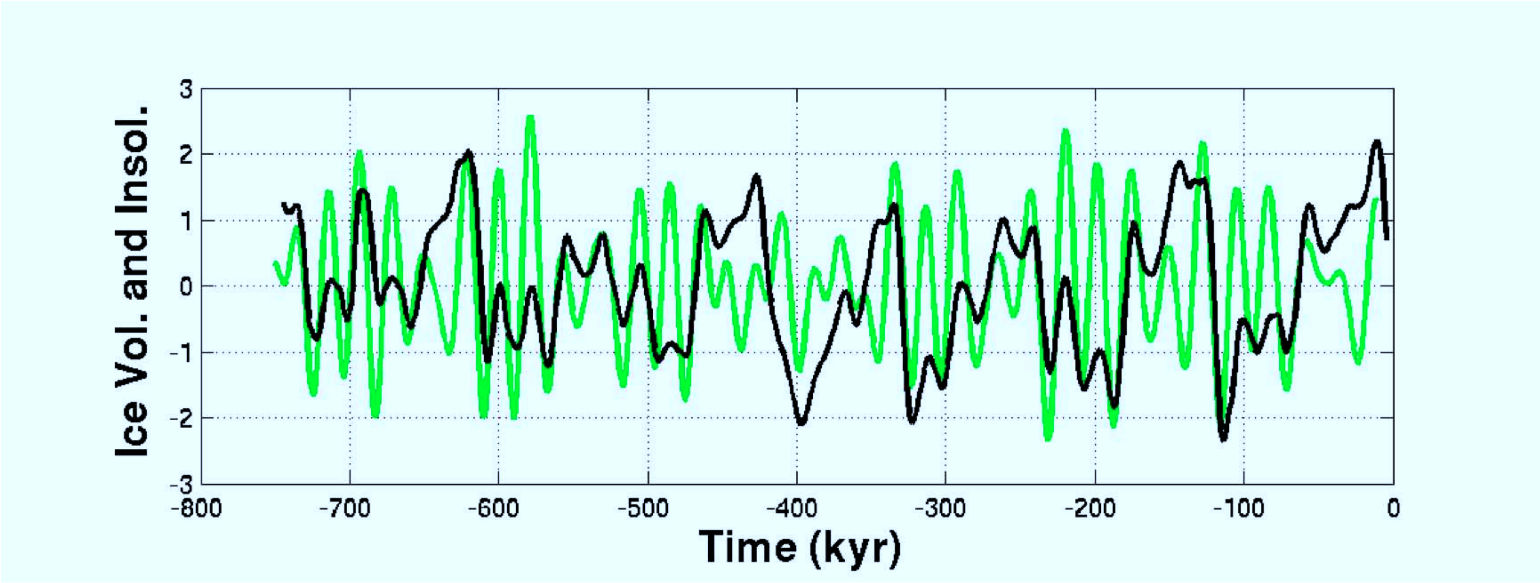
Mostly obliquity



Note neither hypothesis does well for the 100,000 yr world

integrated summer “energy” is in giga Joules per square meter

The SPECMAP ice volume time series
and June insolation at 65N (upside down)



• **maximum correlation of -0.4**
with a 6 kyr lag of ice volume behind insolation

• more ~100 kyr variability in ice volume than in insolation

Next 8 slides are from Gerard Roe

What people say about this

• 6 kyr lag is due to dynamical response of ice sheets

• CO_2 leads ice volume by ~6 kyr
• Tropical temperature lead ice volume by ~6 kyr
=> CO_2/SSTs force climate change

• S.H. temperatures lead ice volume by ~6 kyr
=> S.H. source of deglaciation mechanism

• It takes 6 kyr for climate signal to reach the N.H.
=> role of deep ocean/chemistry

BUT, ice volume is a bad climate variable…

Ice volume evolution equation:

$$\tau >> 2\pi / f$$

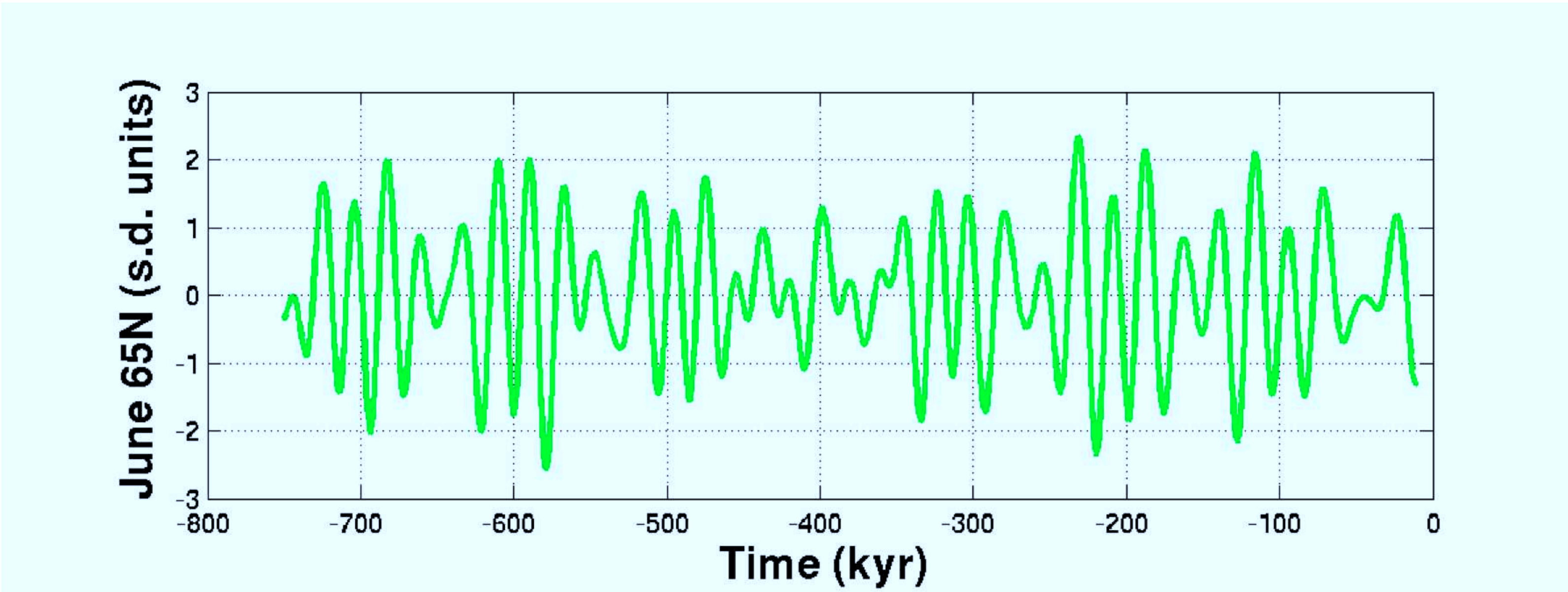
$$\frac{d}{dt} volume(t) + \cancel{\frac{volume(t)}{\tau}} = insolation(t)$$

vs.

$$volume(t) = insolation(t - 7kyr)$$

Rate of change of ice volume

• d(volume)/dt more directly related to high latitude insolation



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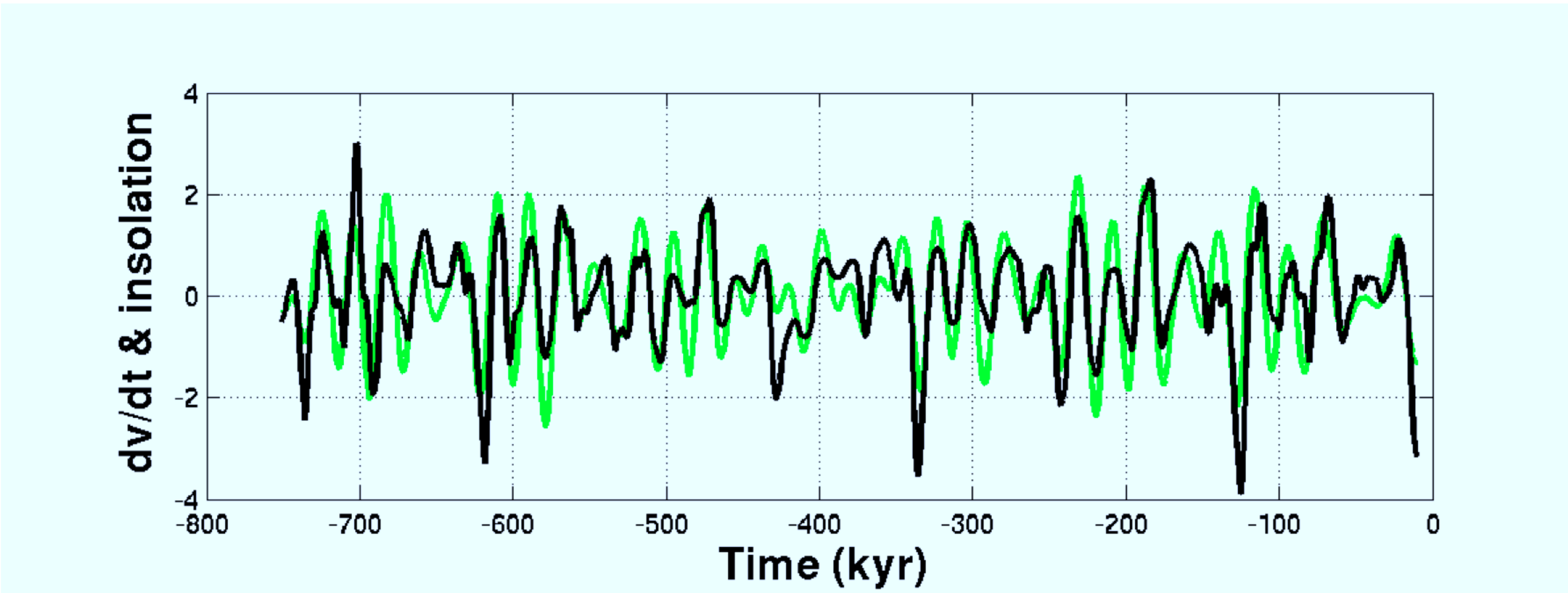


• **maximum correlation of -0.8**
at zero lag

But recall the ice volume is from SPECMAP

Why is this dubious?

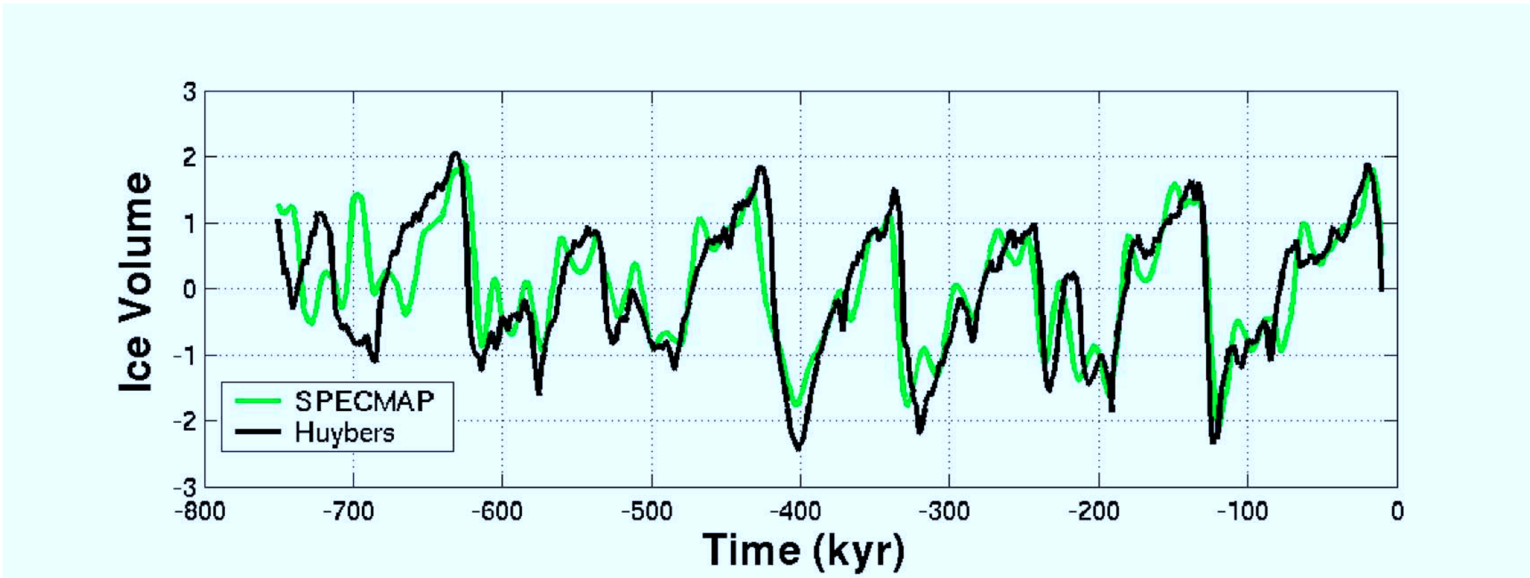
- SPECMAP Ice volume records have been tuned to orbital parameters!

- Date is tuned by maximizing co-variance in
  20 kyr, 40 kyr bands, assuming fixed (& different)
  phases with obliquity and precession.

- So argument linking dv/dt to insolation is nearly circular
  (but not quite)

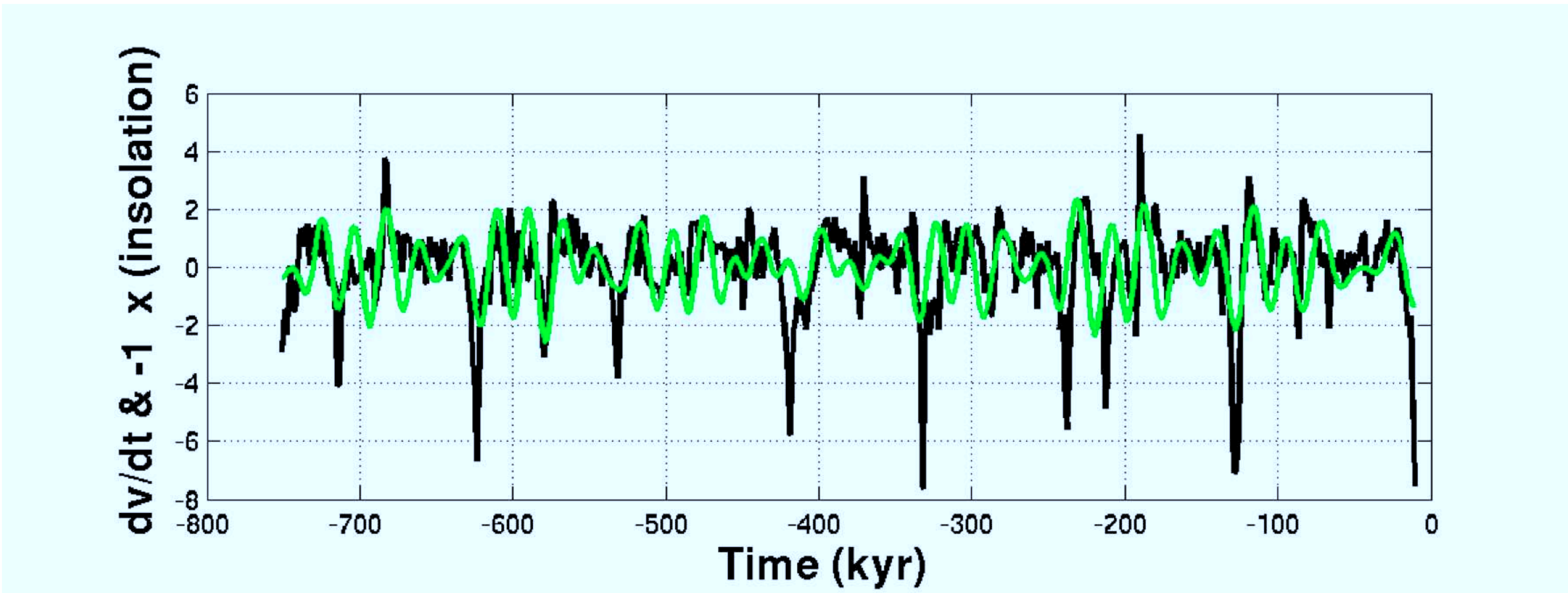
Ice volume record independent of orbital tuning

(Peter Huybers, for his PhD)



Rate of change of ice volume record

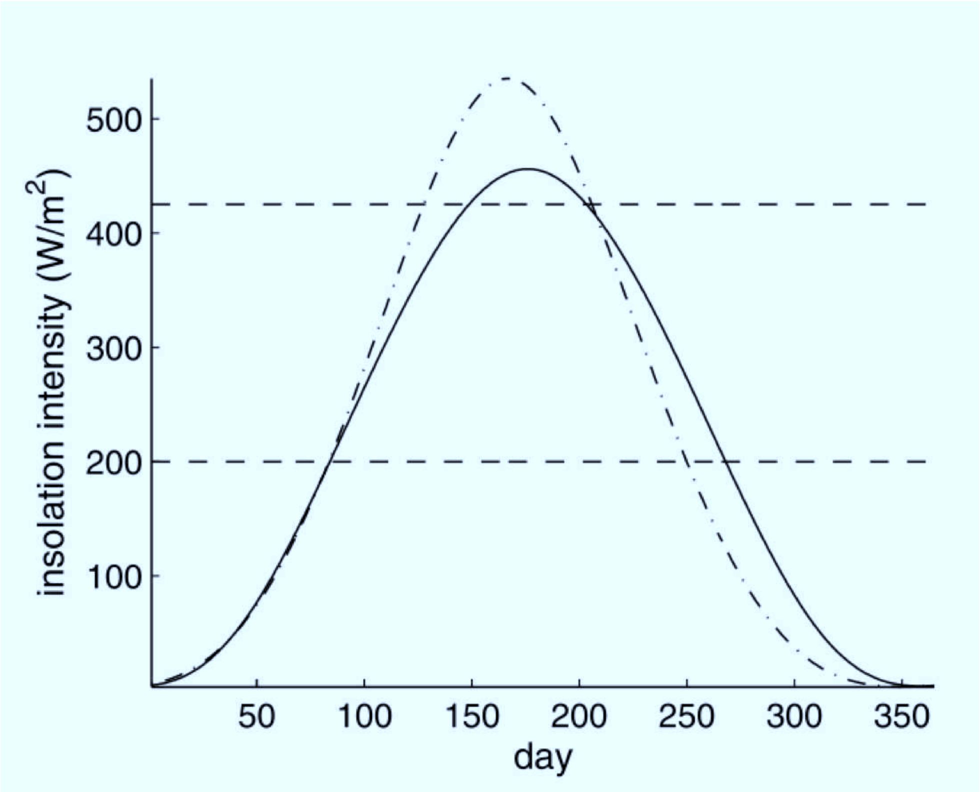
and insolation upside down



• maximum correlation of -0.4

at zero lag

Substantial correlation but failure is greatest at major minima in ice volume… so not explaining 100k ice ages

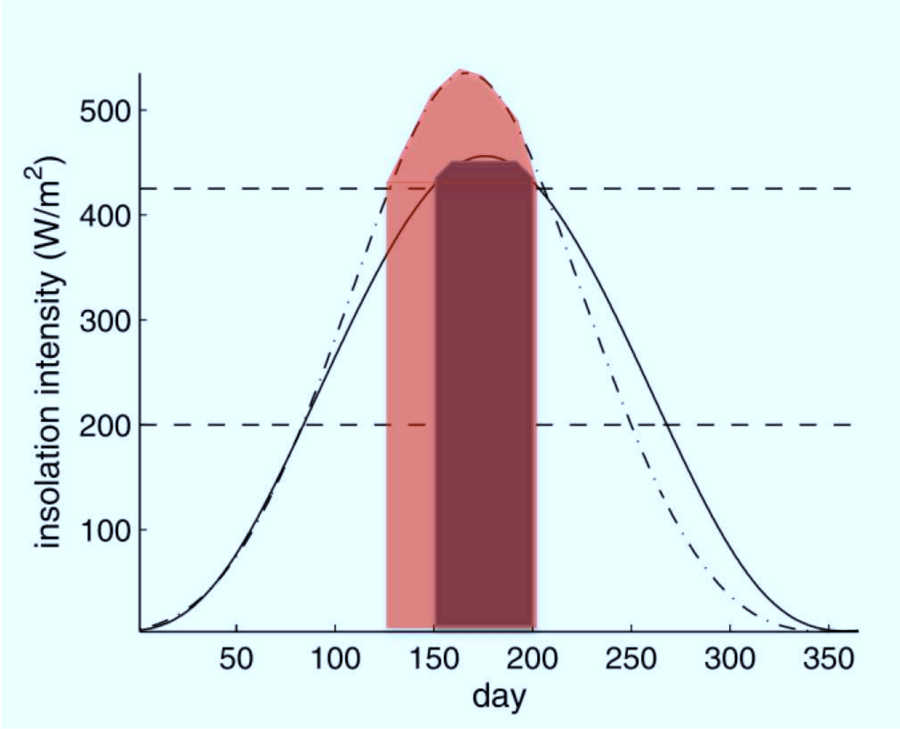


Huybers & Tziperman
2008

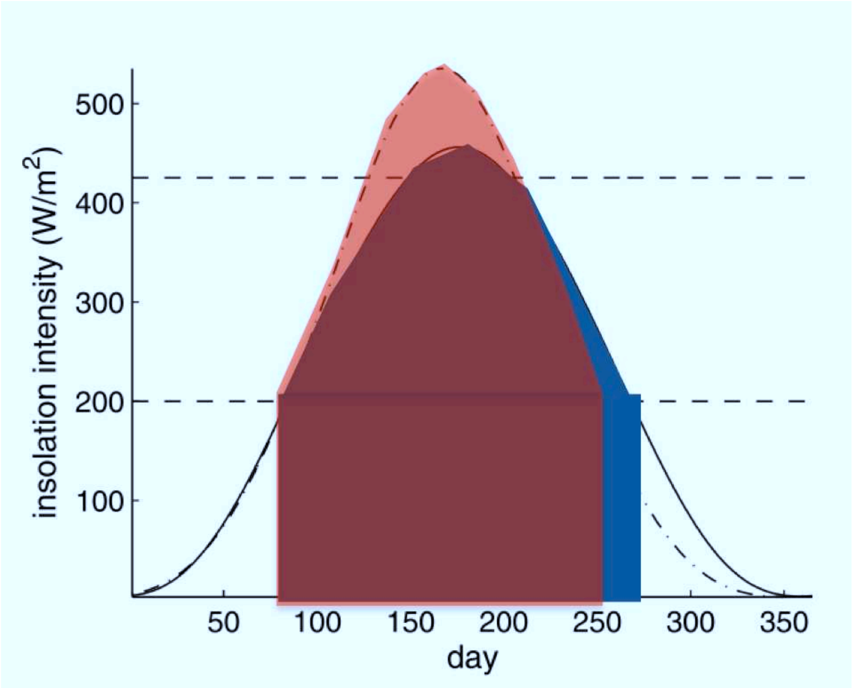
"Summer Energy"

$$J = \sum_{d=1}^{365} \beta_d \Phi_d,$$

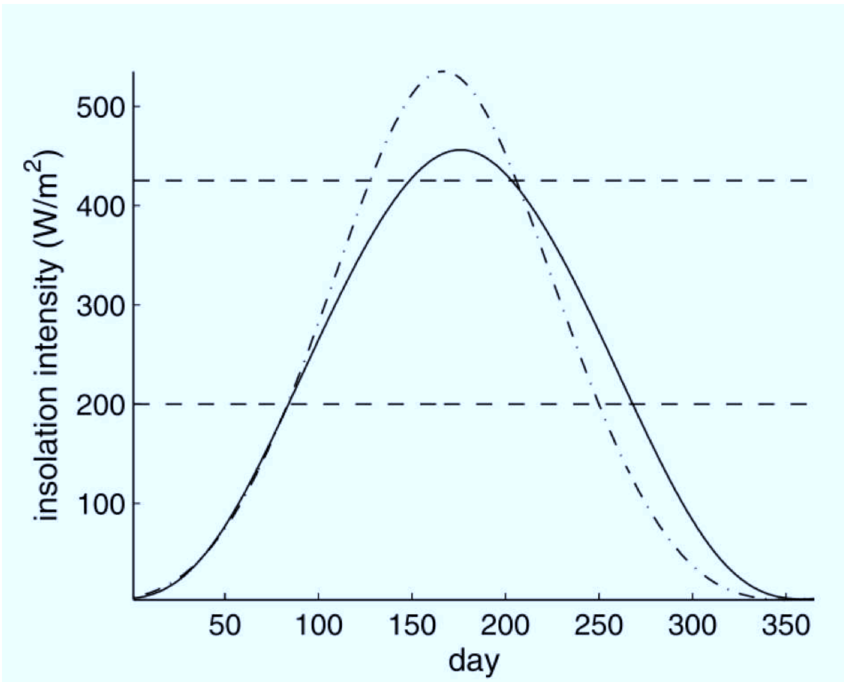
where Φ_d is the daily average insolation intensity, and β_d is one when Φ_d is above a threshold, τ; otherwise, β_d is zero.



If threshold is here, Precession extremes give very different values for J ("intensity" controlled: when perihelion occurs in summer)



If threshold is here, Precession extremes have little affect on J
Get "counterbalancing" between intensity and duration control

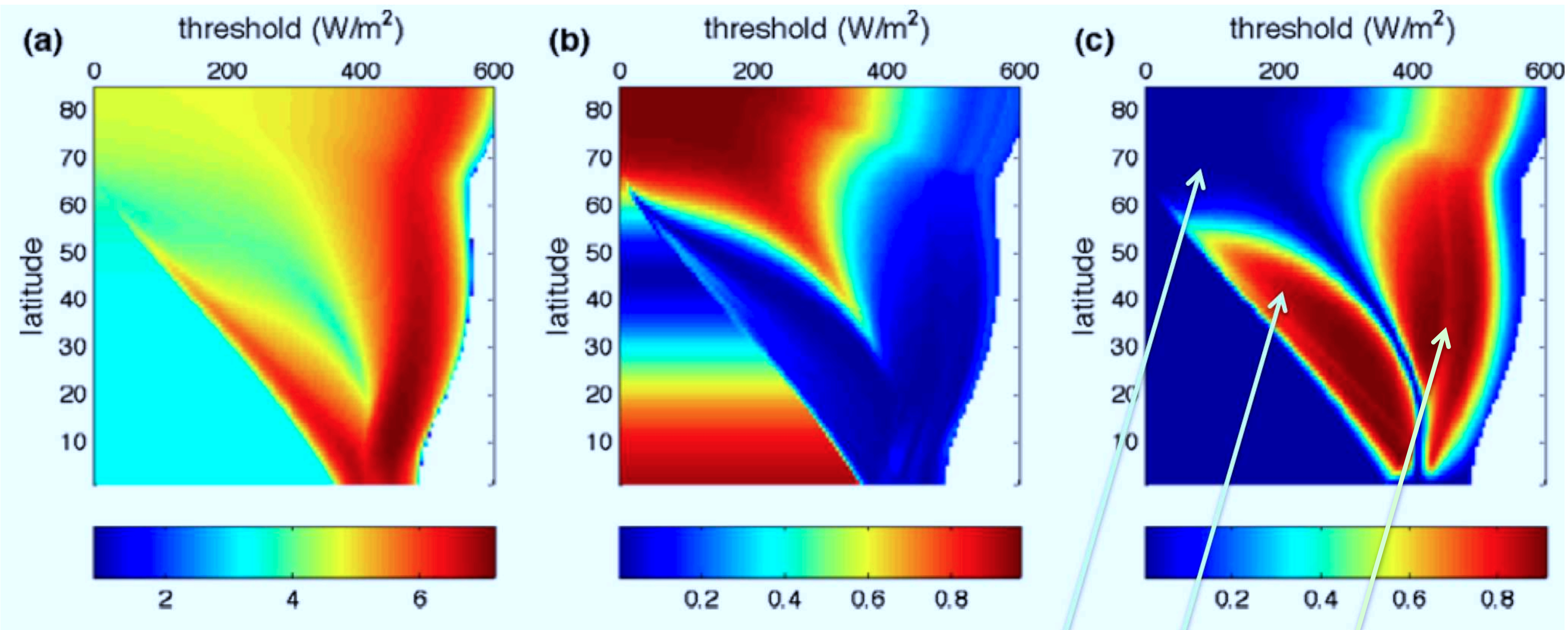


Even lower thresholds would make duration of summer control J, occurs when apehion occurs during summer. Another way for precession to have a large effect.

Variance of J all periods

Obliquity periods

Precession periods



Remember low threshold -> small effect from precession

Duration of summer controlled

Intensity of summer controlled

Model Schematic

2-layer EBM plus 2D thermodyn. ice sheet

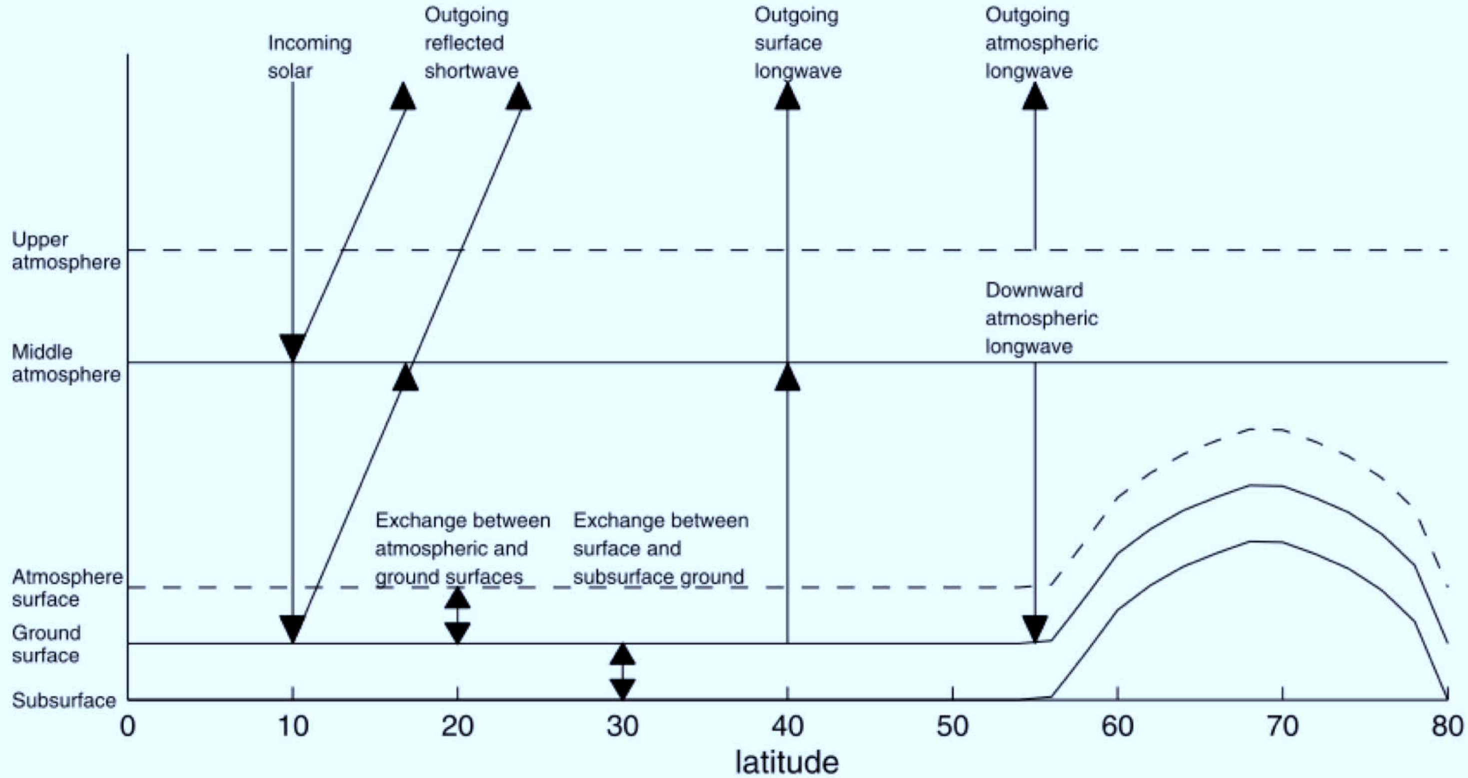
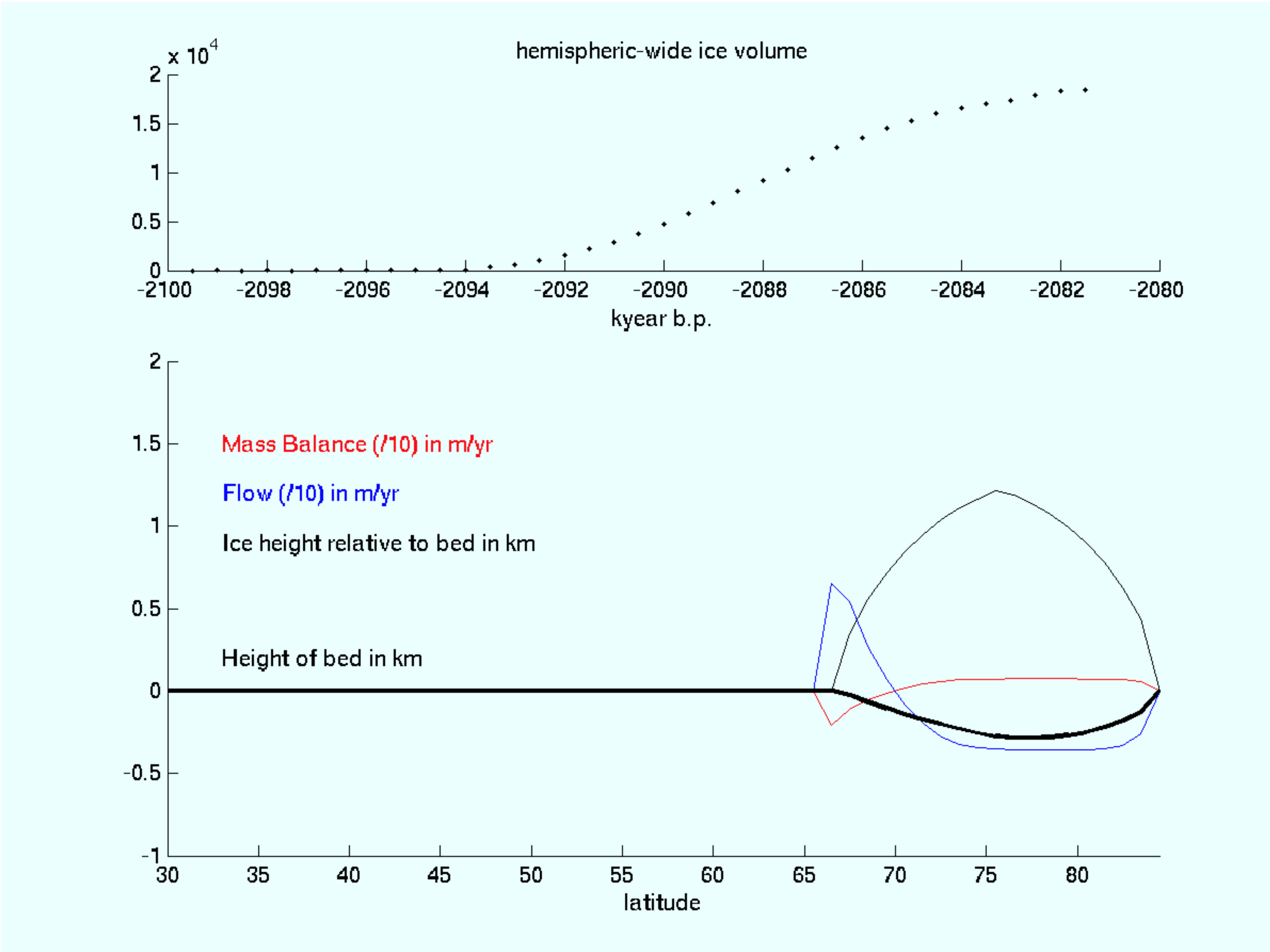


Figure A1. Schematic of the energy fluxes. Levels from top to bottom are the upper and middle atmosphere, atmospheric surface layer, ground/ice surface, and subsurface. Arrows indicate locations at which radiative, diffusive, or turbulent heat fluxes are absorbed or reflected. Note that the atmosphere radiates upward only at the upper atmospheric level. The model has 1° resolution in latitude. Surface and subsurface boxes are represented as either ground or ice and, in this case, an ice sheet extends equatorward to 55°. For the sake of visual clarity, the *y* axis is not drawn to scale.

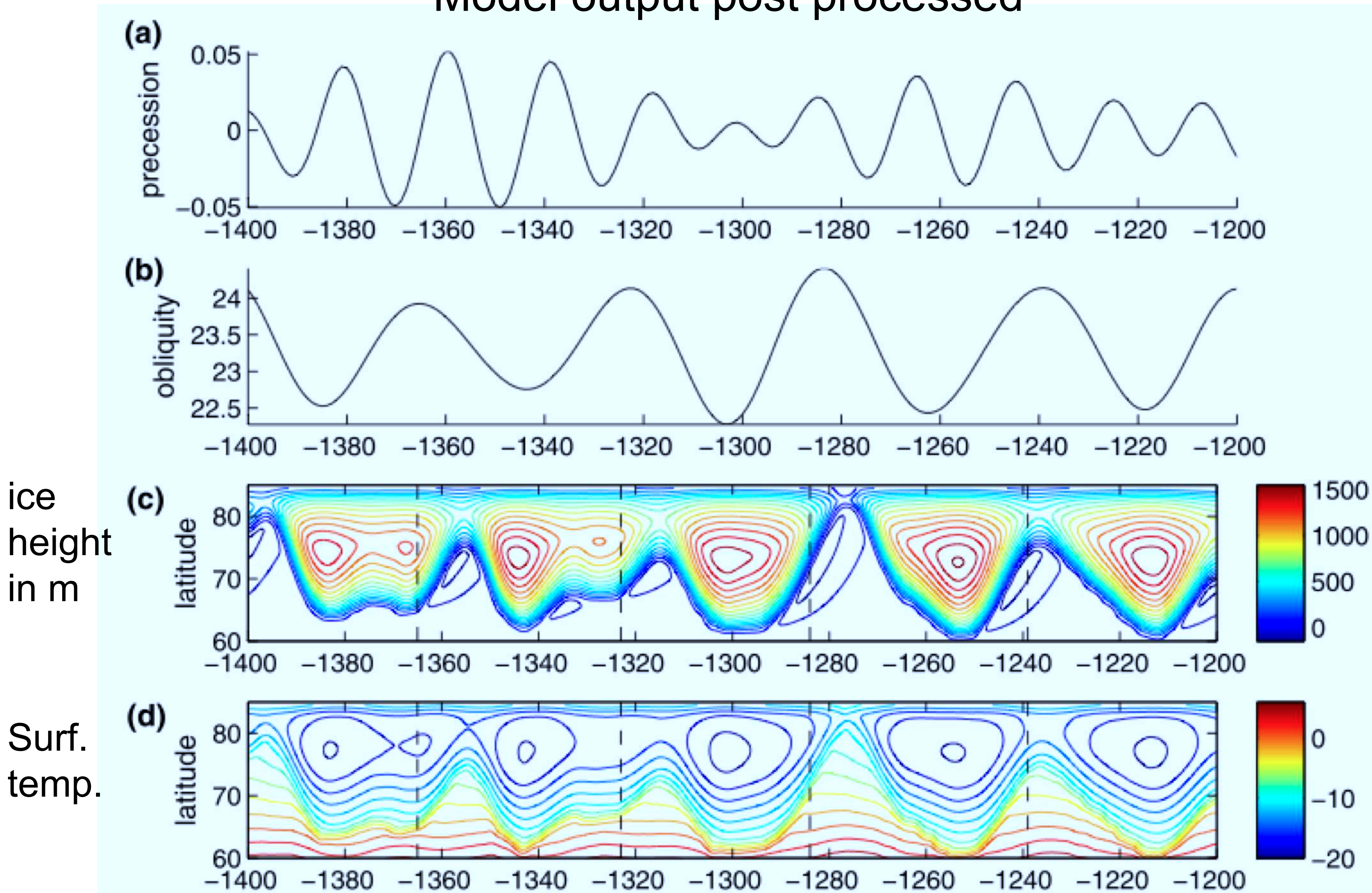
ice flowing to 85N is assumed to calve into the ocean and melt, surface is otherwise bedrock

- Uses model fluxes to compute ablation, not PDD since PDD is to much like summer energy. Hence can test summer energy hypothesis.
- Precipitation rate is fixed, it falls as snow if atm surface temp is below freezing

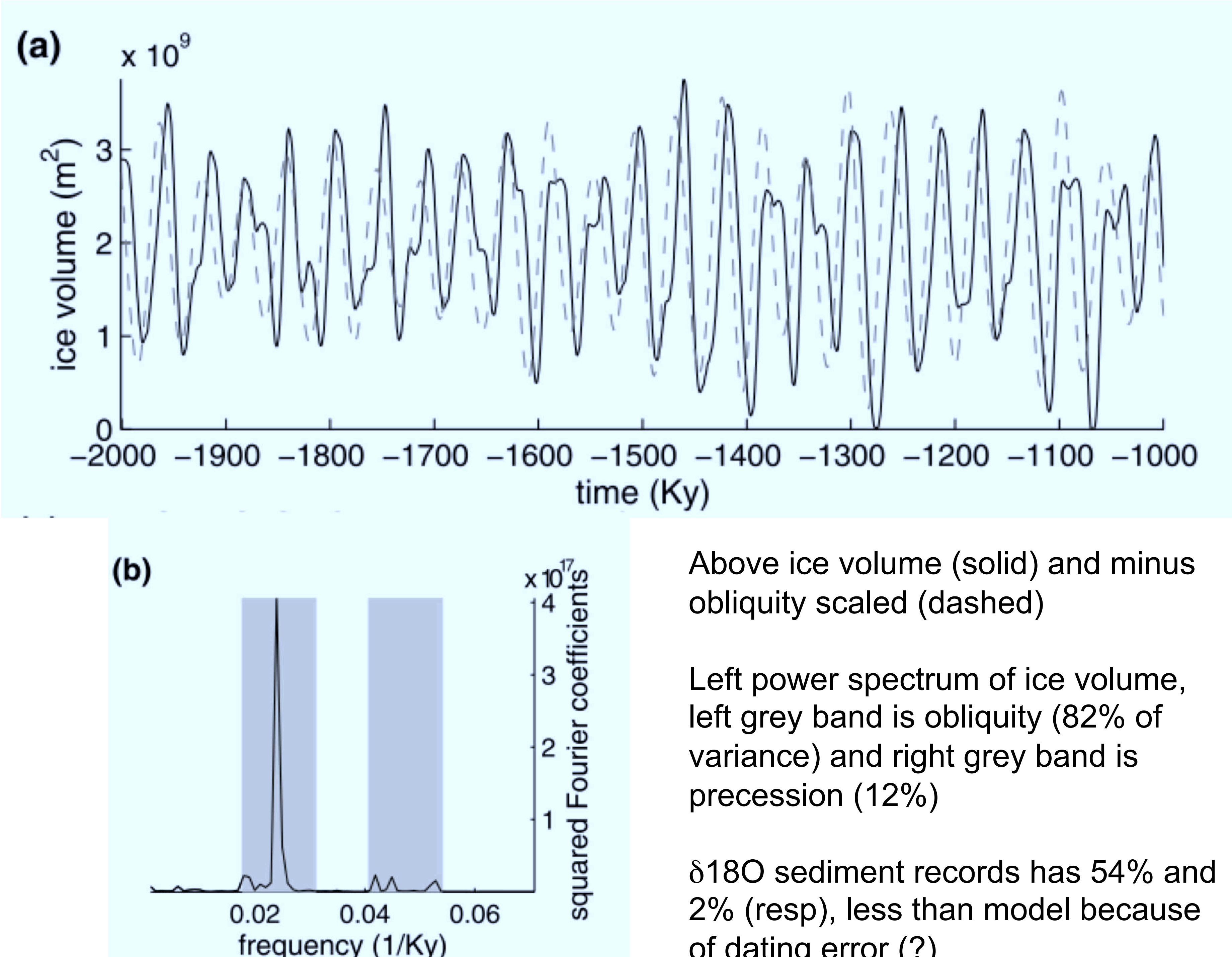
The model looks like this as you run it.



Model output post processed



Time in ky b.p.



Above ice volume (solid) and minus obliquity scaled (dashed)

Left power spectrum of ice volume, left grey band is obliquity (82% of variance) and right grey band is precession (12%)

δ18O sediment records has 54% and 2% (resp), less than model because of dating error (?)

Table A2. Parameters Used for the Ice Sheet and Sediment Model

Variable	Value	Units	Description
n	3		exponent in Glen's law
A	7.7×10^{-29}	$1/(Pa^3\ s)$	deformability of the ice
T_b	5000	years	bed depression timescale
ρ_s	2390	kg/m^3	saturated bulk sediment density
ρ_b	3370	kg/m^3	bedrock density
ϕ_s	22°	degrees	angle of internal friction
D_o	2.5×10^{-14}	1/s	reference sediment deformation rate
m	1.25		exponent in sediment stress-strain relationship
u_o	3×10^9	Pa/s	sediment reference viscosity
h_{sed}	10	m	thickness of sediment layer
H_{eq}	0	m	equilibrium height above sea-level
T_b	5000	years	bed relaxation time constant

[48] The ice-sheet component of the model is zonally averaged and a function of meridional distance, y, and height, z. It utilizes a common shallow-ice approximation [e.g., *van der Veen*, 1999], assuming that deformation occurs only as a result of horizontal shear stress and that stress and strain are related by Glen's law. The ice is assumed isothermal and incompressible, and the evolution of its thickness is governed by the continuity equation,

$$\frac{\partial h}{\partial t} = B - \frac{\partial}{\partial y}(\bar{u}h). \tag{A9}$$

Here h is the thickness of the ice sheet, B represents the surface mass balance, and $\bar{u}$ is the vertically averaged

h is thickness from bed to top

velocity is

$$u(z) = \frac{(\rho g)^n}{n-1} A \left(\frac{\partial (h+H)}{\partial y} \right) \cdot \left((h+H-z)^{(n+1)} - (h+H)^{(n+1)} \right) + u_b, \qquad \text{(A11)}$$

where n is the exponent in Glen's flow law and A governs the deformability of the ice. A is known to depend on

h is thickness from bed to top
H is bed depression (H<0)

2 ρ_i n missing/errors

velocity is

$$u(z) = \frac{(\rho g)^n}{n-1} A \left(\frac{\partial(h+H)}{\partial y}\right) \cdot \left((h+H-z)^{(n+1)} - (h+H)^{(n+1)}\right) + u_b, \tag{A11}$$

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