Historical variability of glaciers

Lithograph from “Norway and its glaciers: visited in 1851” by James David Forbes

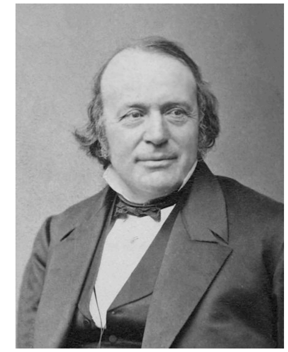
Nigardsbreen, Norway “Nine farm glacier”

Historical variability of glaciers

Lithograph from “Excursions in the Alps 1842” by James David Forbes

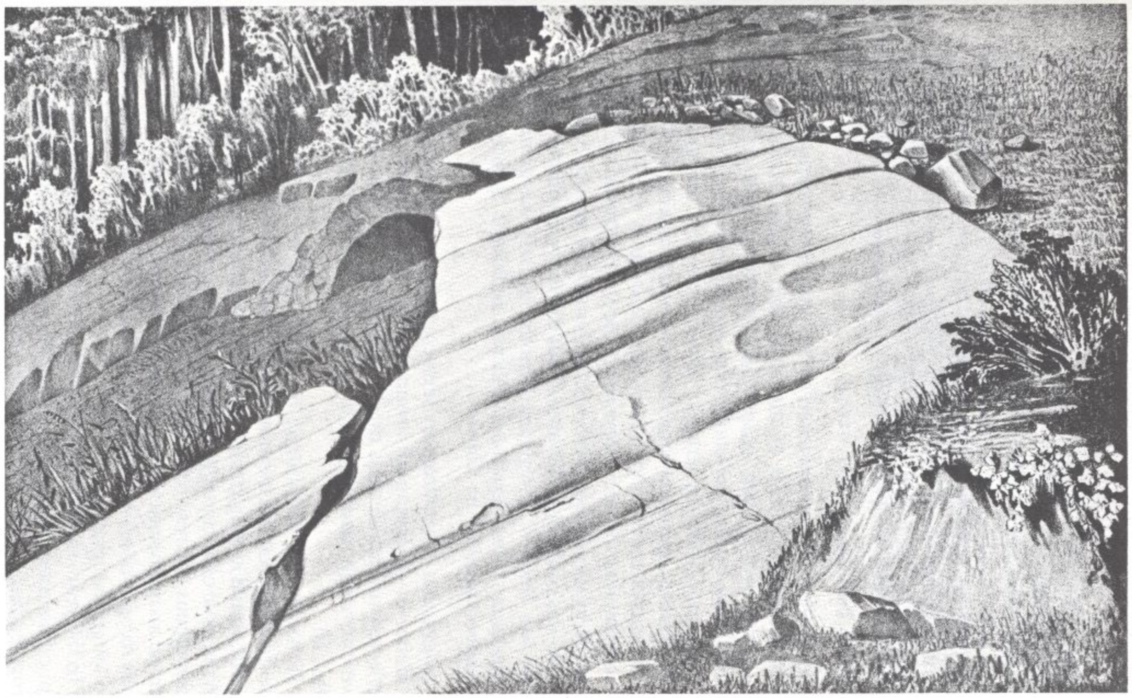
Grossser Aletsch Glacier, 1842

Louis Aggasiz



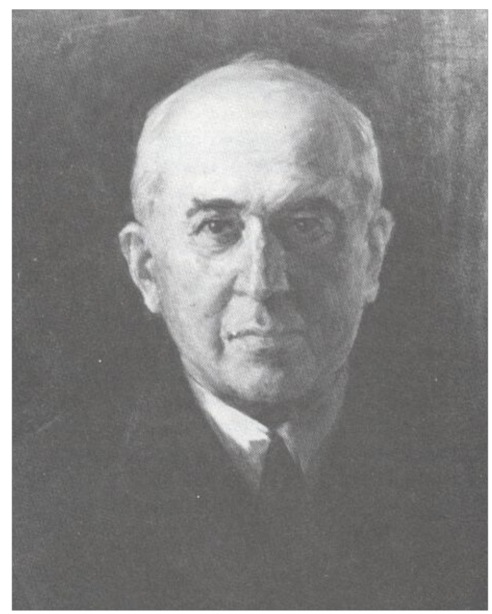
J.D. Forbes

Ice Age research



Rev. Prof. Buckland

Milankovitch cycles,
Milankovitch curves,
Milankovitch insolation,
Milankovitch theory,
Milankovitch hypothesis….
?



Milutin Milankovitch

Imbrie amd Imbrie, 1979

Milutin Milankovitch (1879 - 1958)

“I do not consider it my duty to give an elementary education to the ignorant, and I have also never tried to force others to apply my theory, with which no one could find fault.”

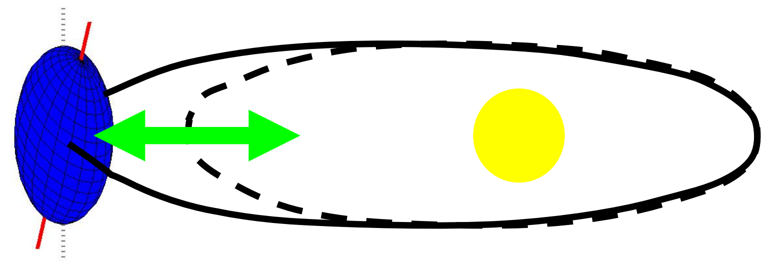
“Such an assertion can only come from someone with amazing courage, since he dares to write of things about which he knows nothing.”

(Milankovitch, 1941)

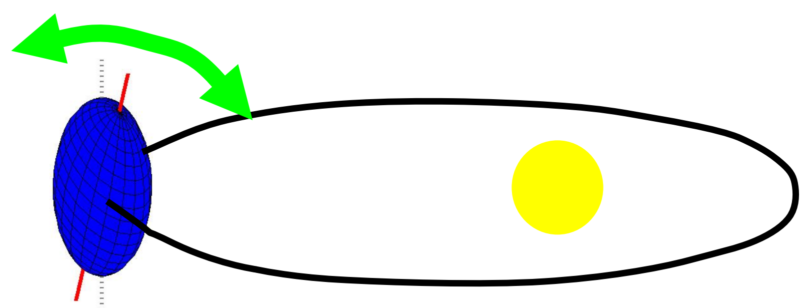
Orbital parameters

- Earth's orbit varies over time due to influence of the Sun, Jupiter, and the Moon.

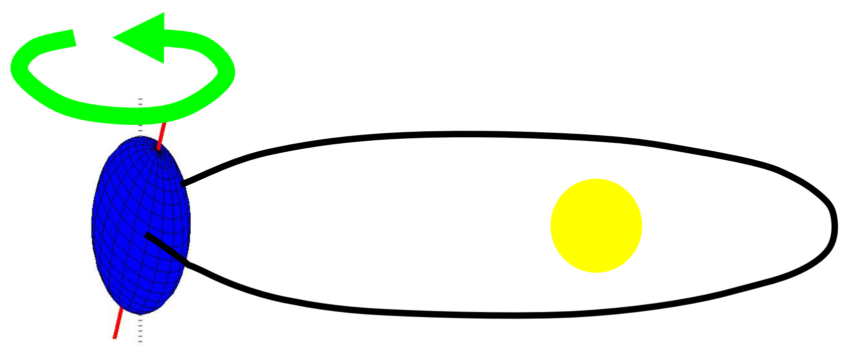
- **Eccentricity** (ellipticity)
  ~100 kyr, 400 kyr



- **Obliquity** (tilt)
  ~41 kyr



- **Precession** (wobbly top)
  ~19, 23 kyr



Note also Kepler’s law’s

1. The orbit of every planet is an ellipse with the Sun at a focus.

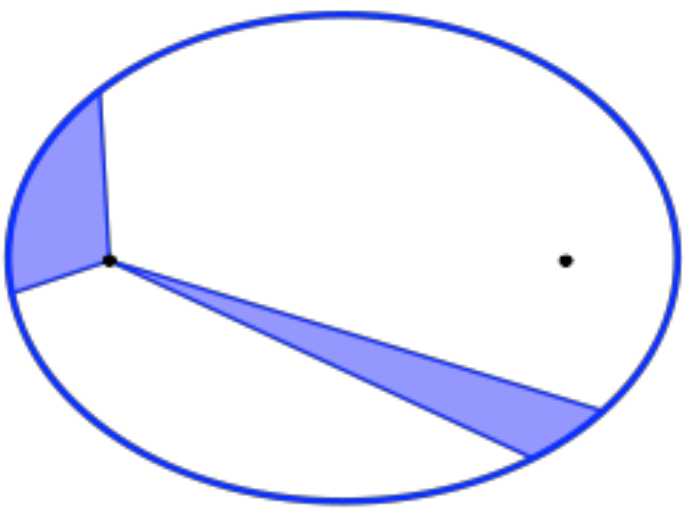
2. A line joining a planet and the Sun sweeps out equal areas during equal intervals of time.

3. The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.

Johannes Kepler, 1571-1630

Are all a consequence of Newtonian gravitation

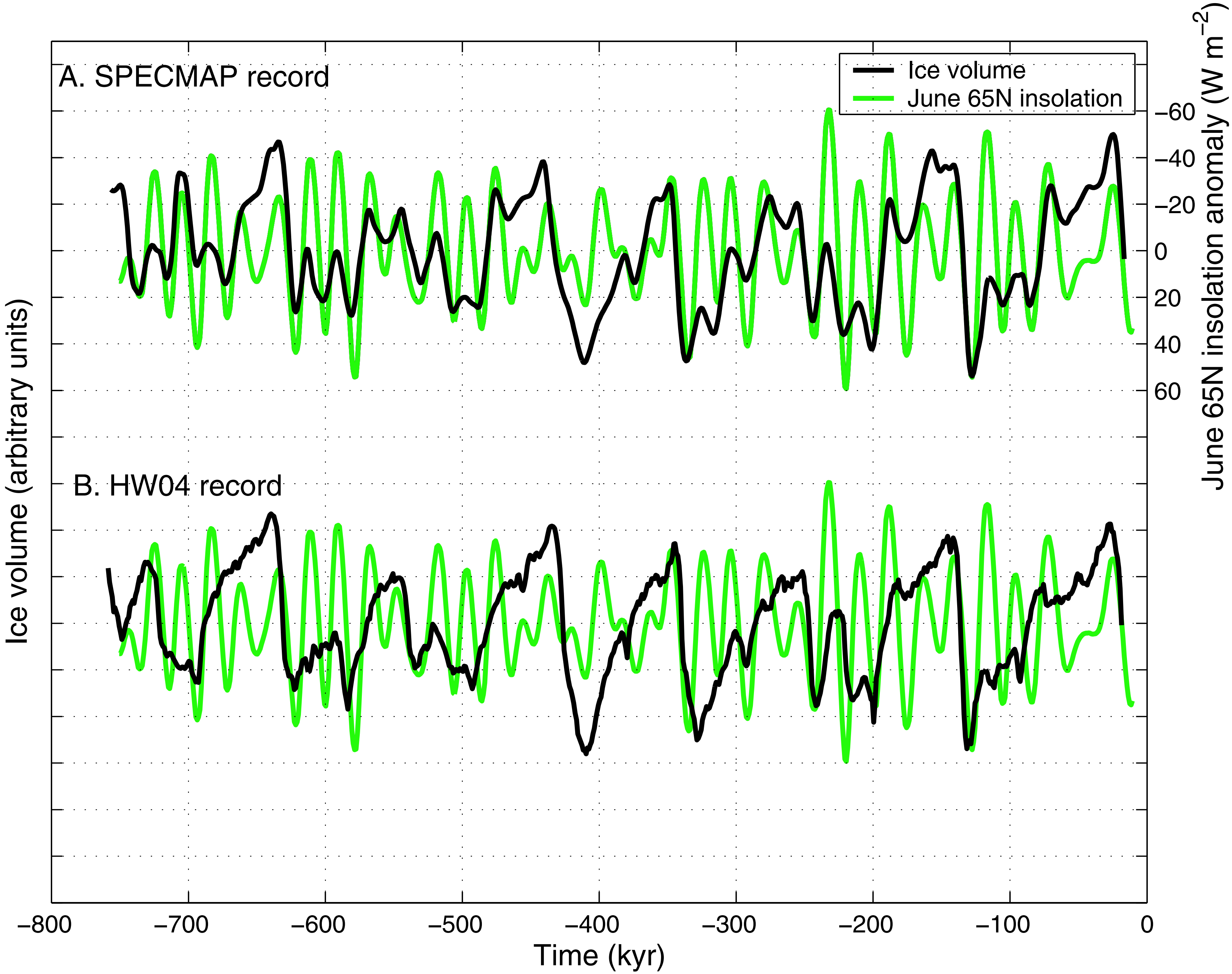
Principia 1687 (also calculus, laws of motion, tides, planetary masses, comets, precession of equinoxes, etc.)



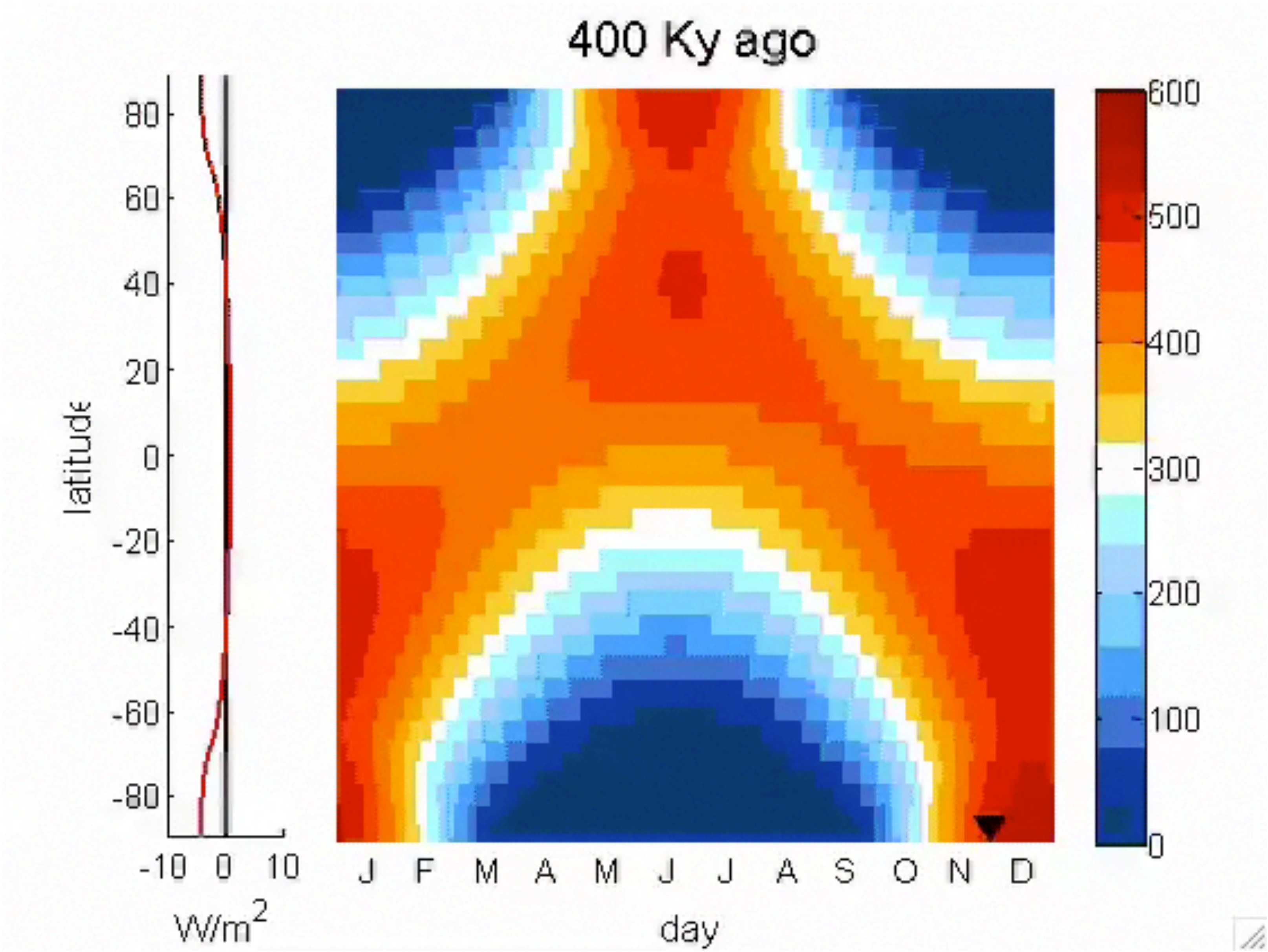
zip round when close,
slow down when far away

Important for seasonally-integrated aspects of climate

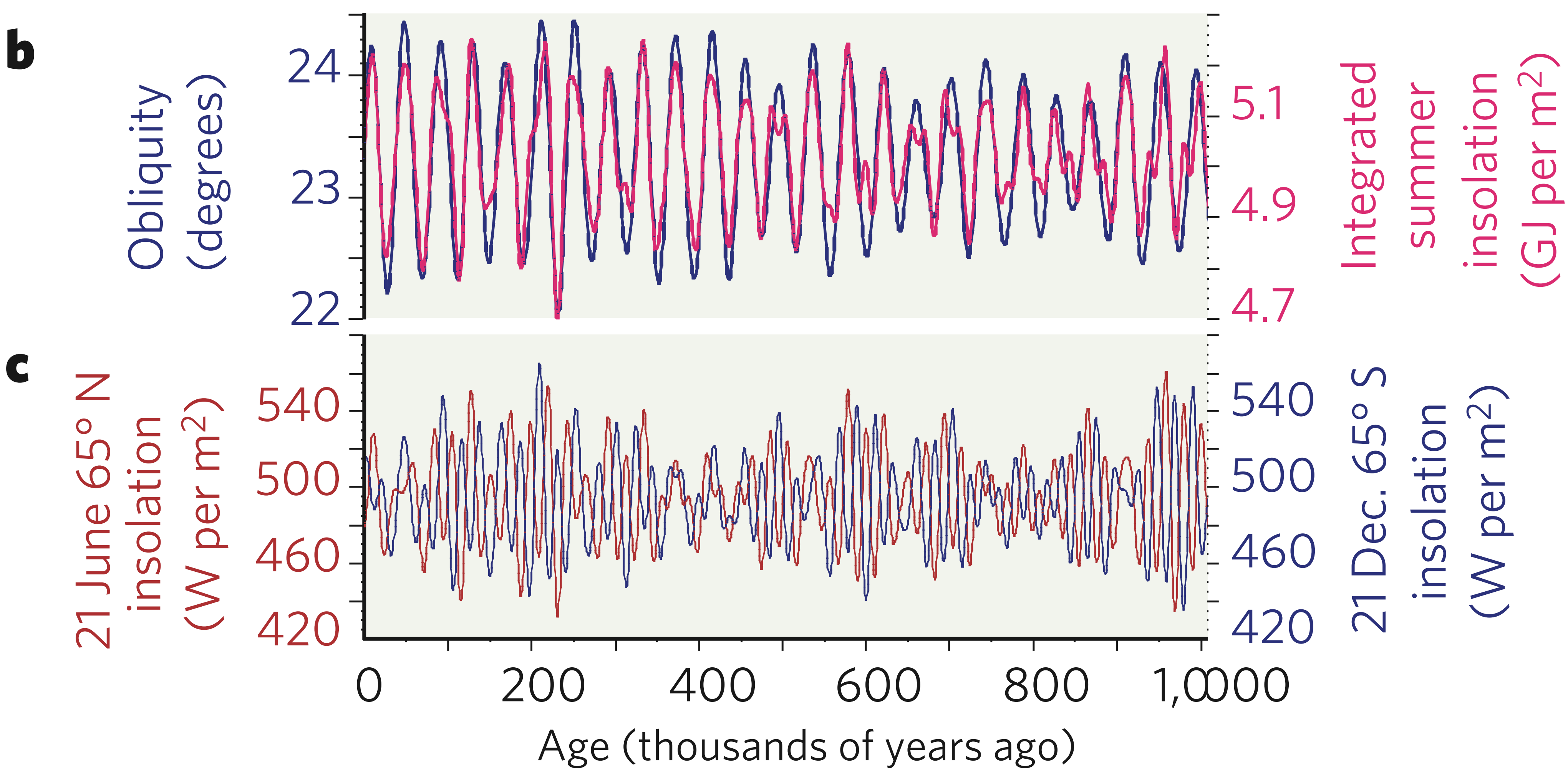
Insolation variations at 65N - Summer Solstice



Insolation variations over the last 400,000 years



Peak summer vs. Integrated summer insolation



Raymo & Huybers, 2008

Which is more important for ablation?

Milutin Milankovitch (1879 - 1958)

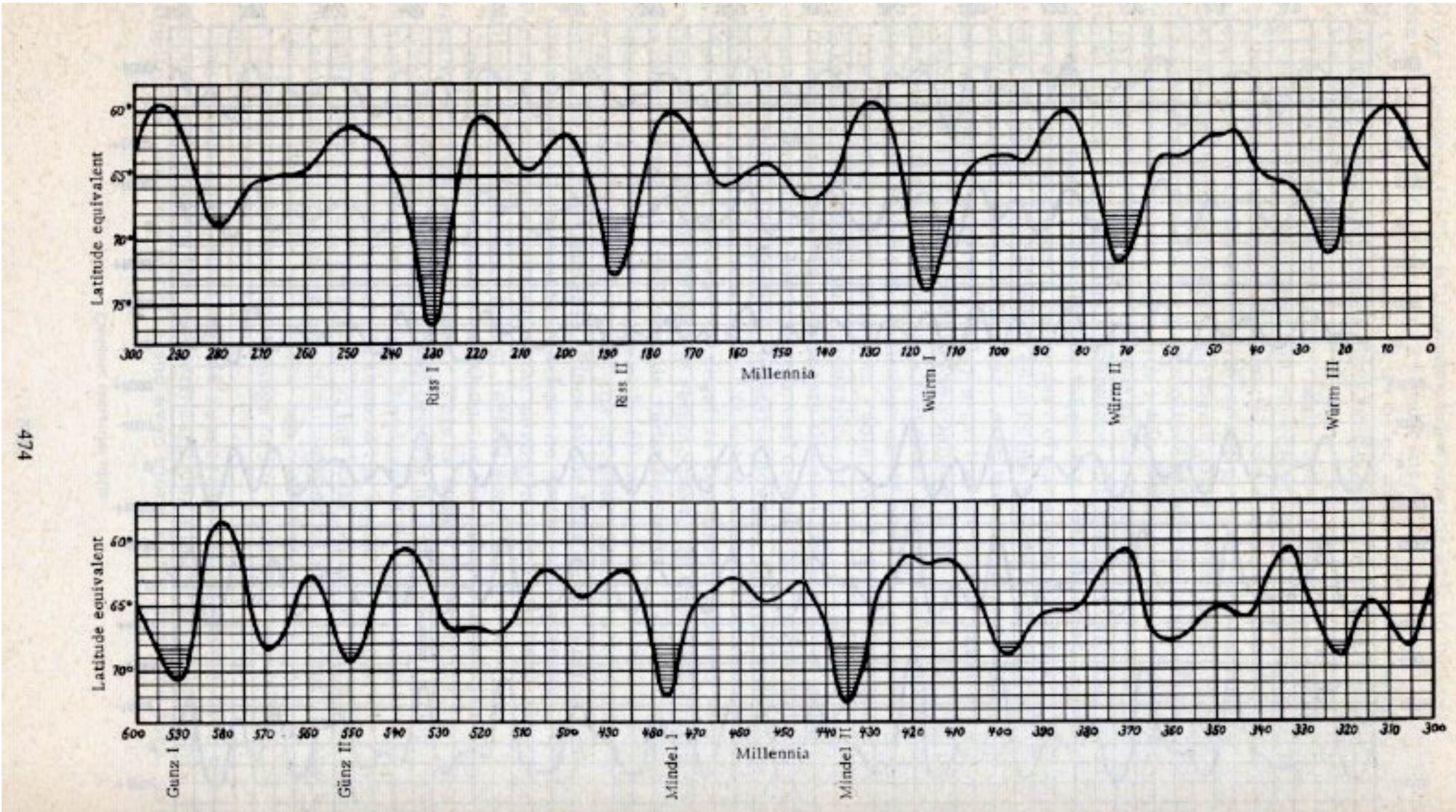


FIGURE 57. The secular march of the summer insolation for 65° North represented by latitudinal oscillations

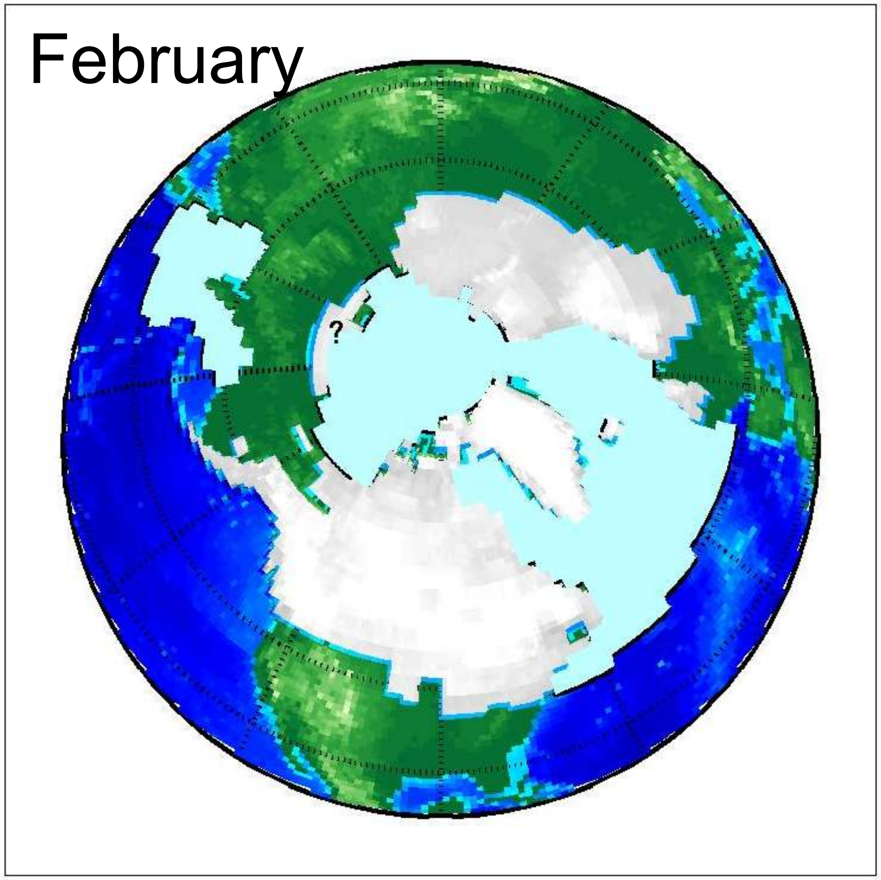
(Milankovitch, 1941)

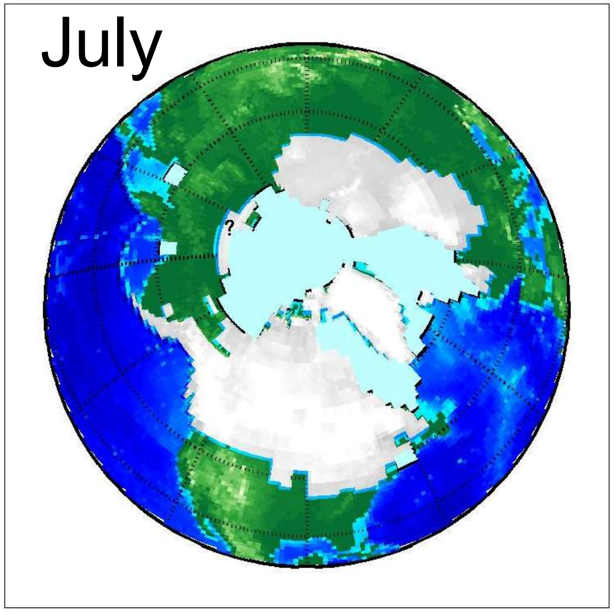
- Glaciations correspond to summer insolation minima…

  Koppen and Wegner critical

What does an ice age look like?

- Reconstruction of land and sea ice 21,000 years ago



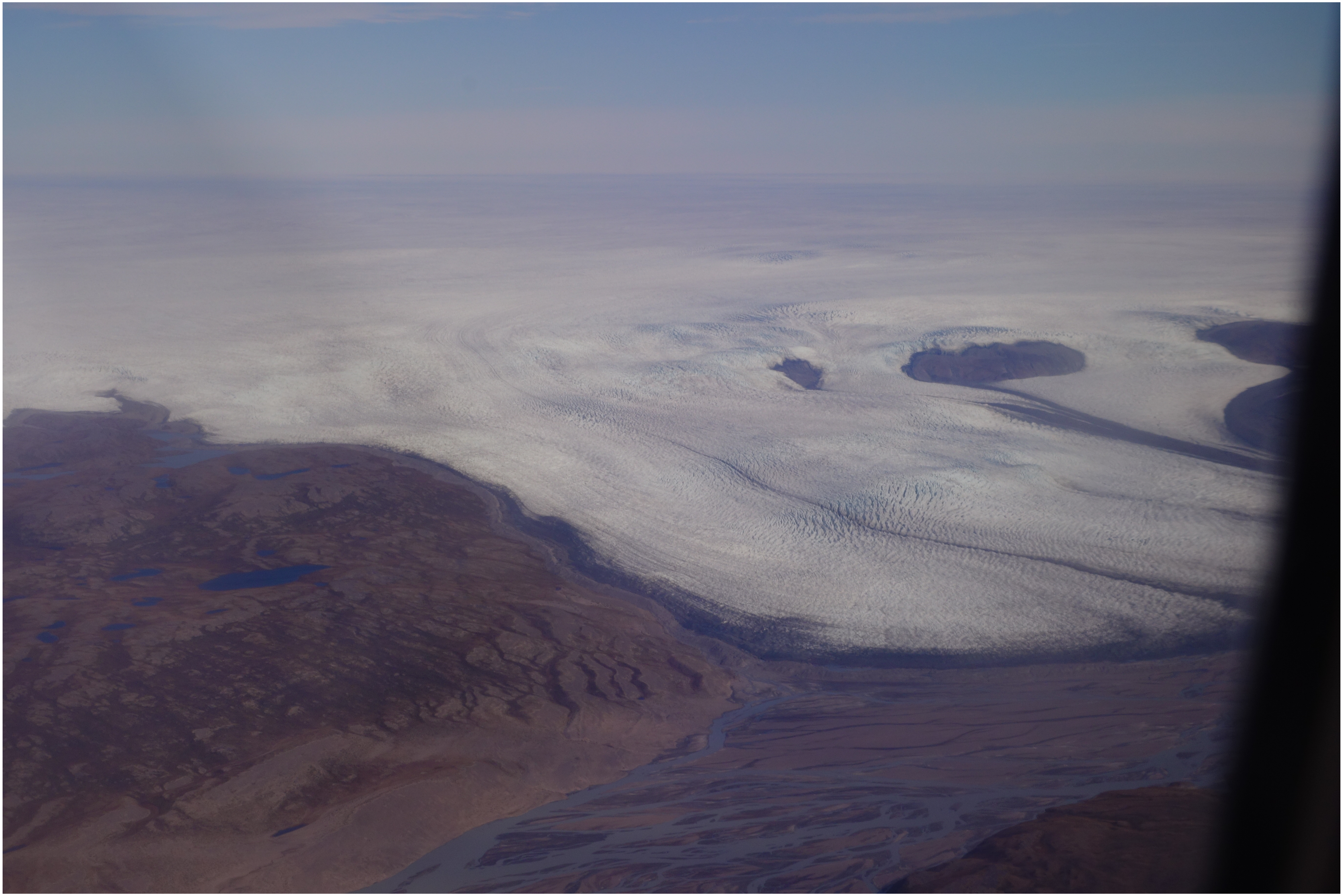


CLIMAP reconstruction

What does an ice age look like?

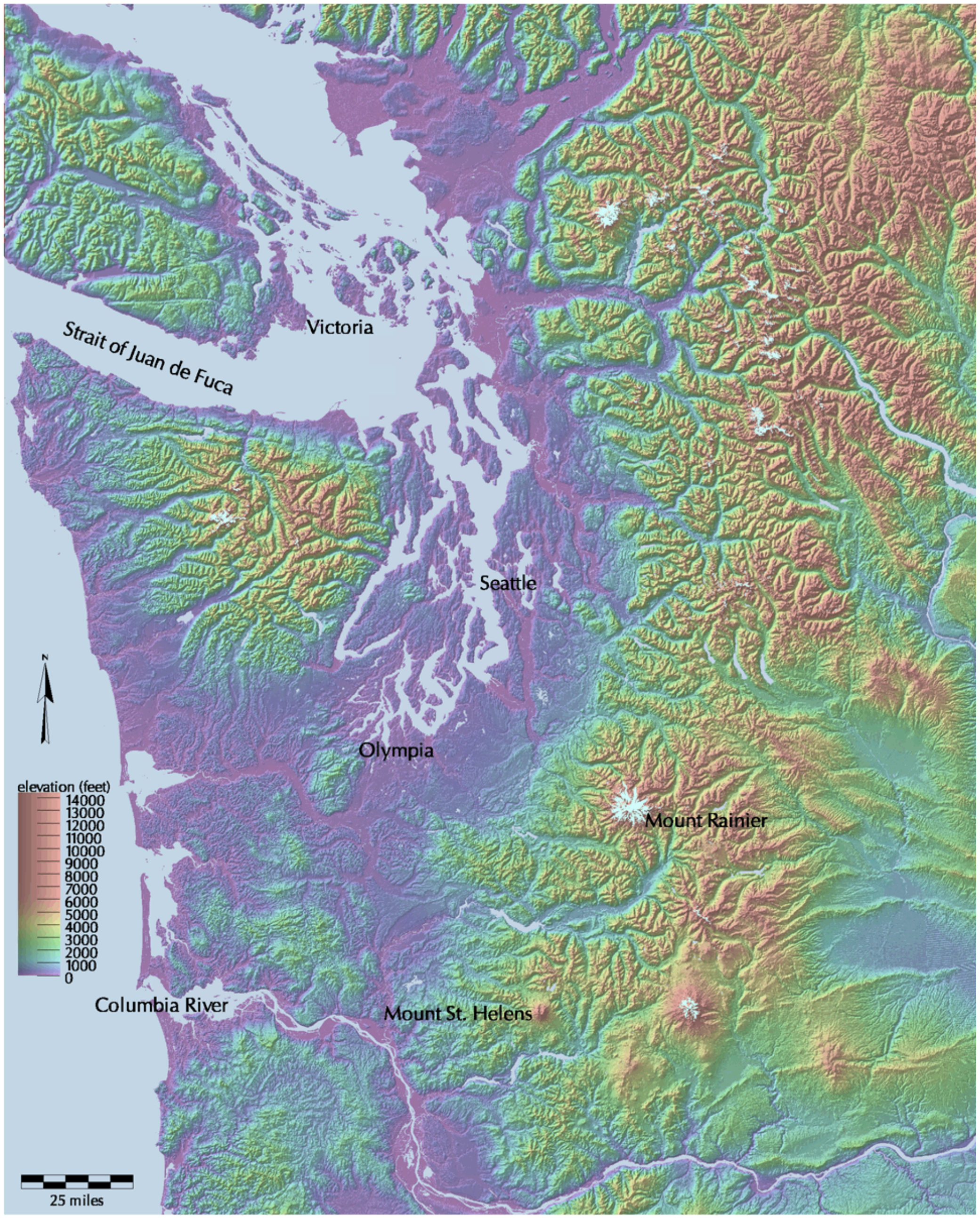
(Eastern Greenland
-Steve Porter)

Western Greenland

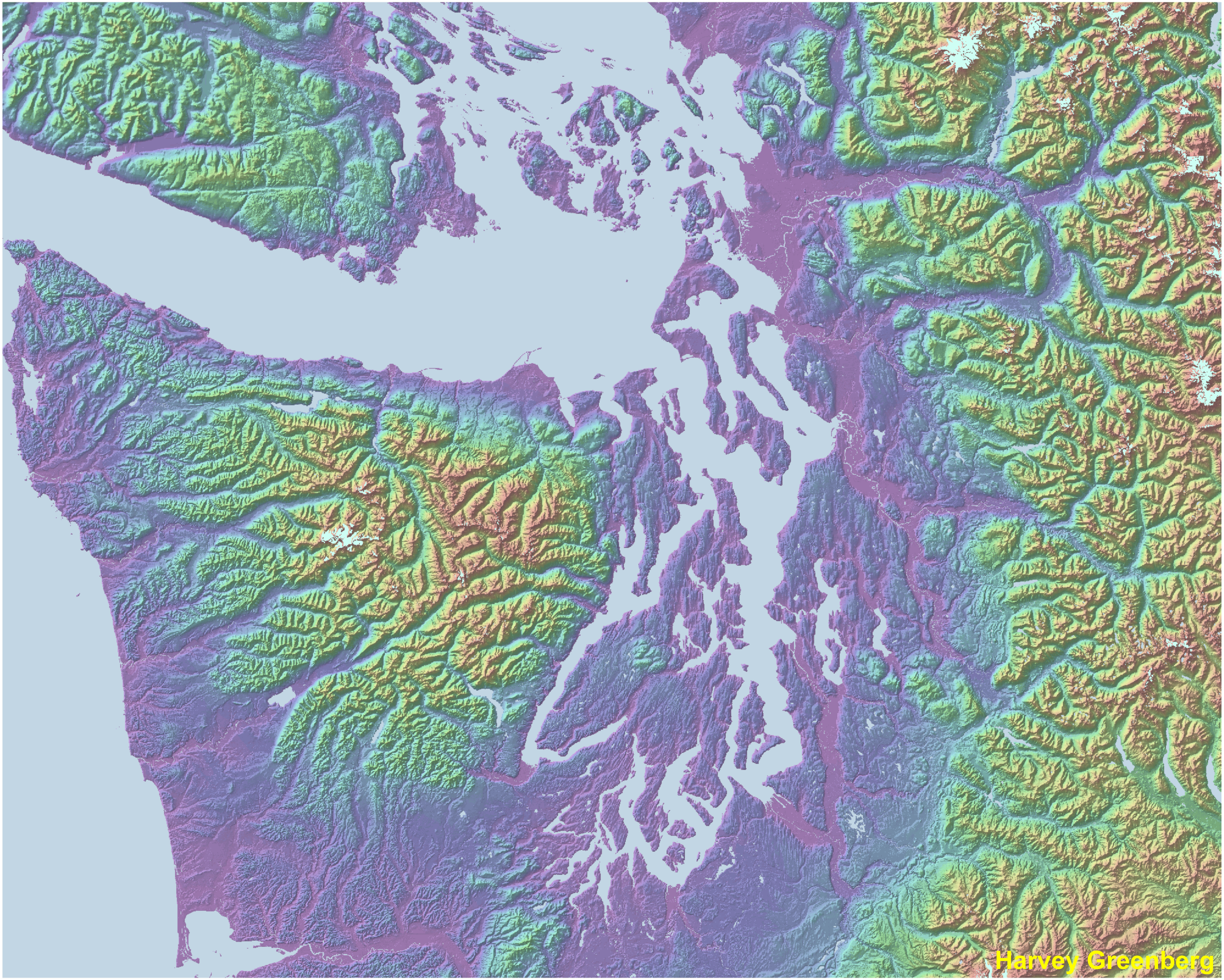


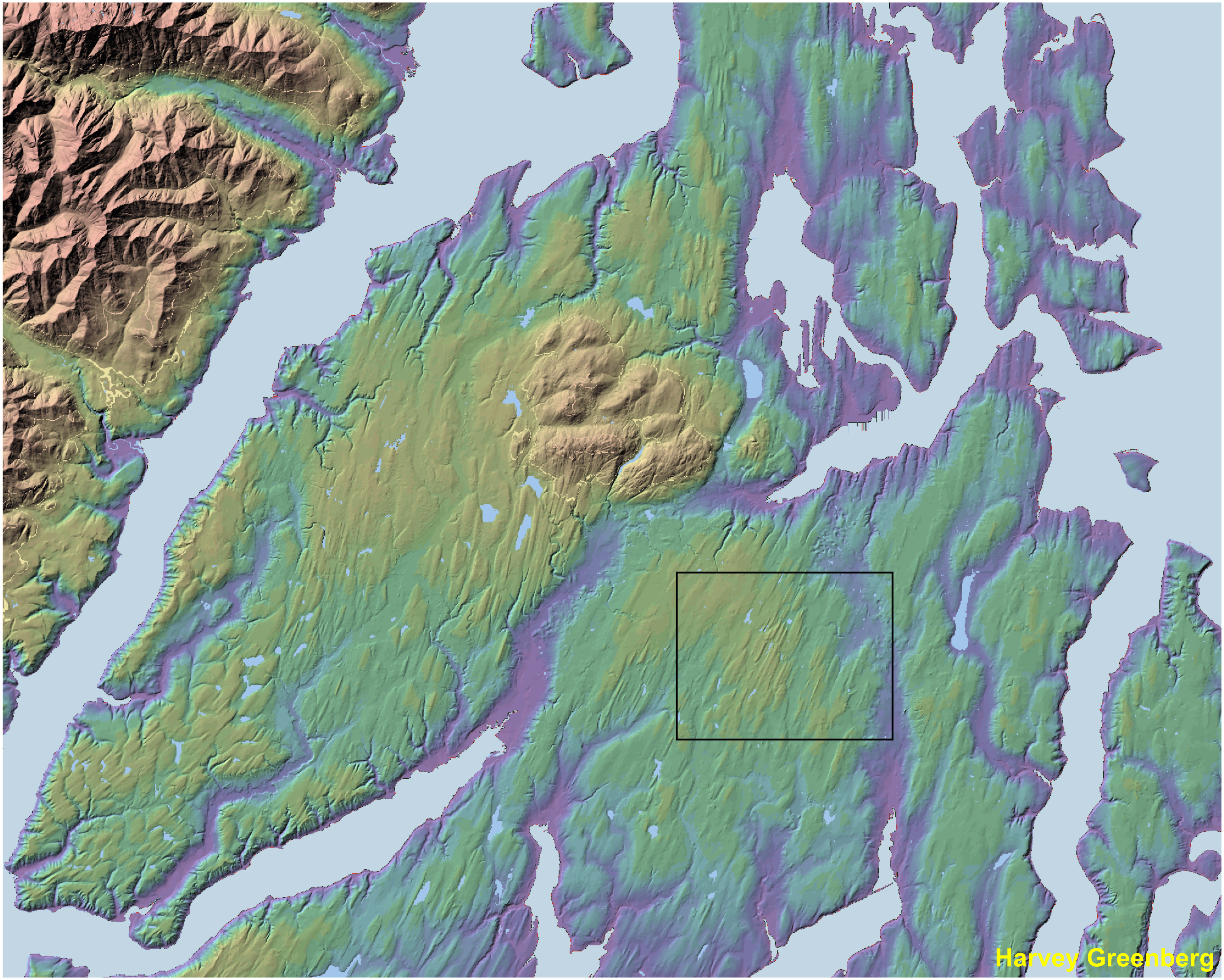
What does an ice age look like?

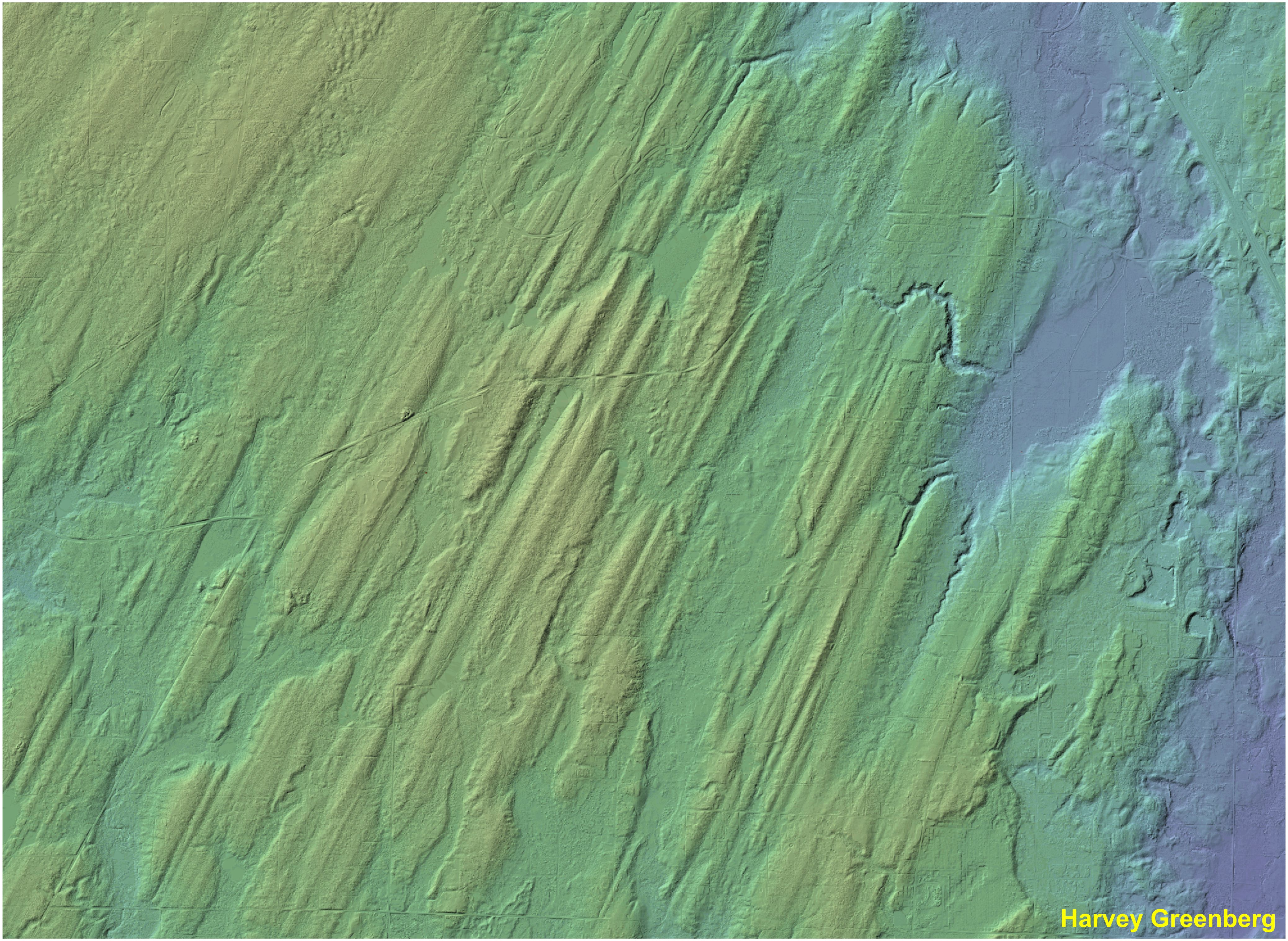
Puget sound lobe

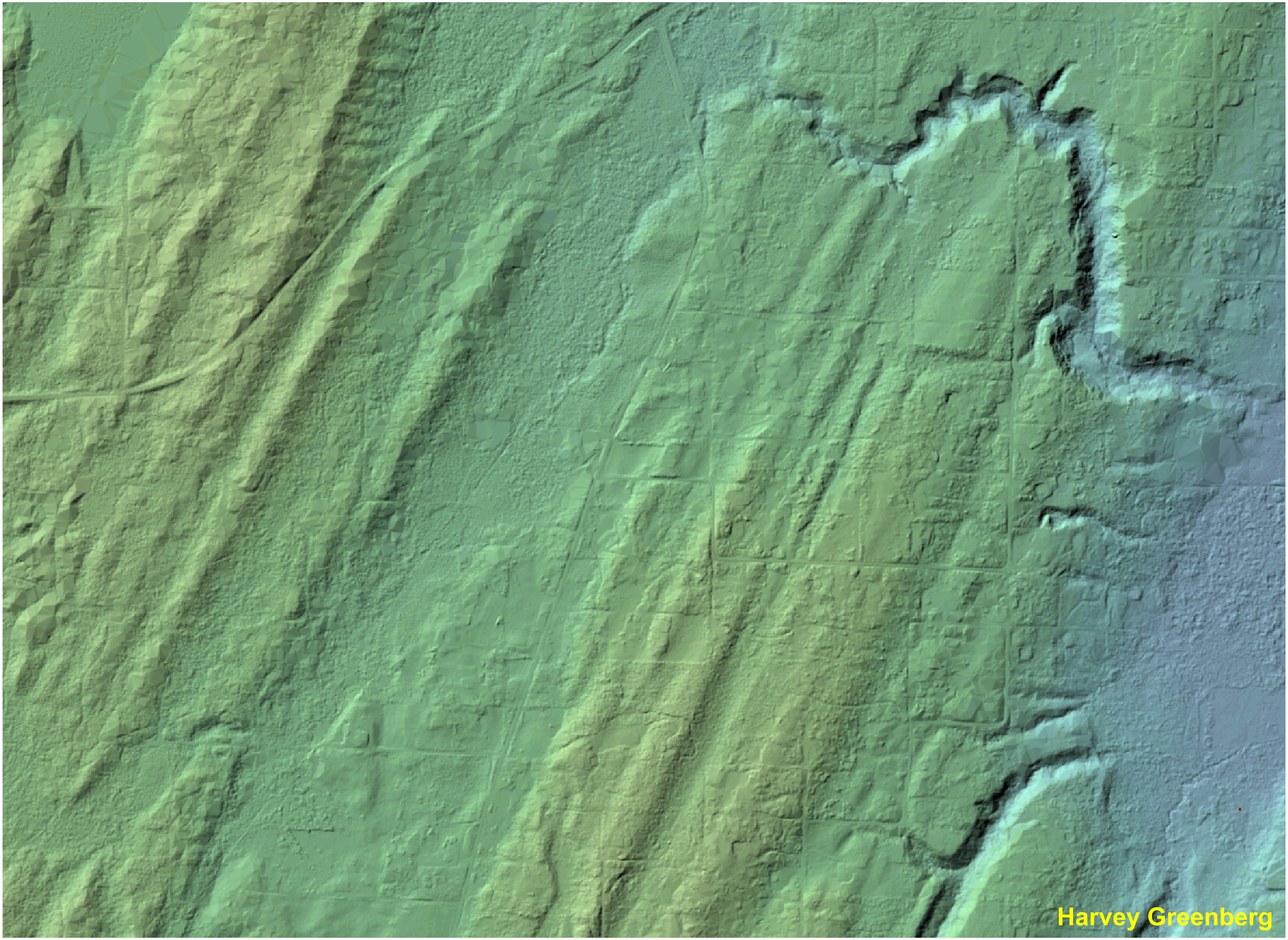


Ralph Haugerud
Harvey Greenberg

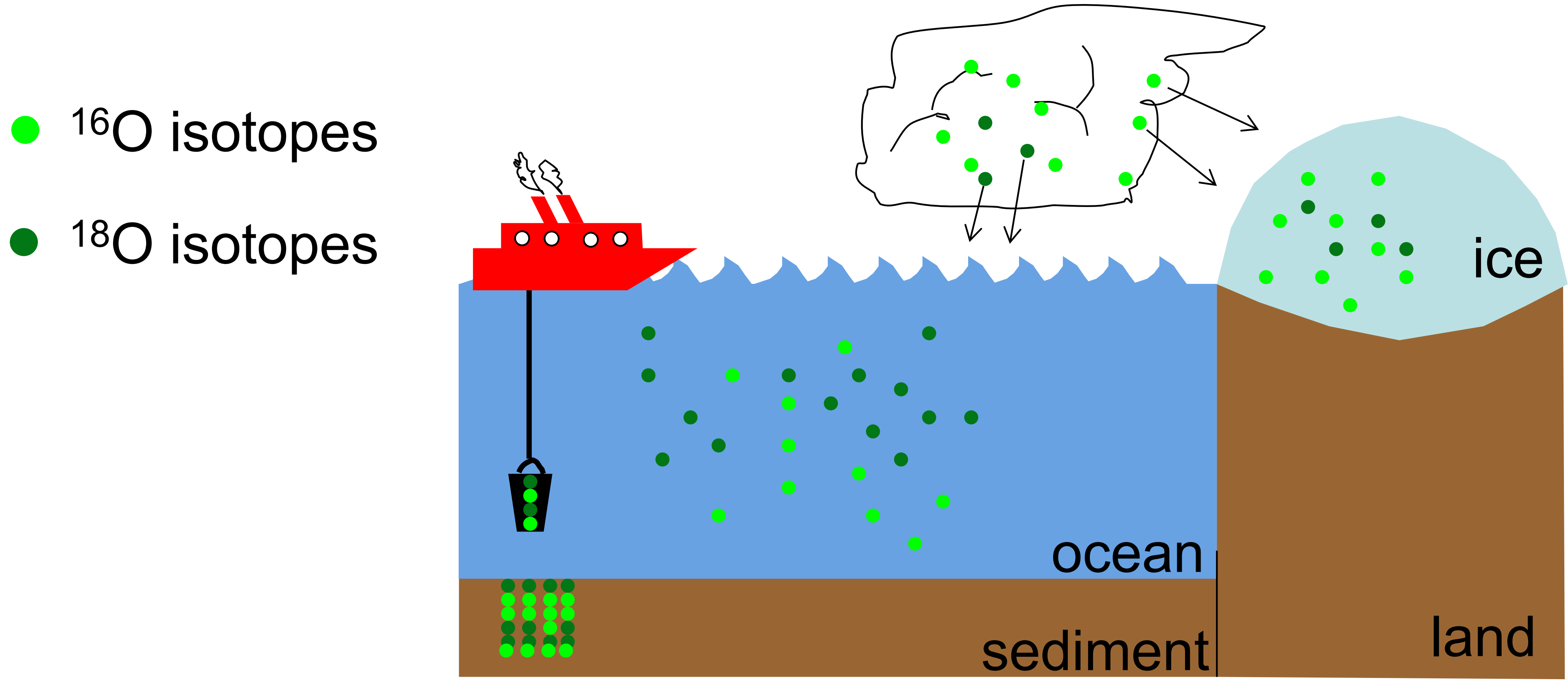

Harvey Greenberg


Harvey Greenberg


Harvey Greenberg


Harvey Greenberg

Inferring global ice volume in the past



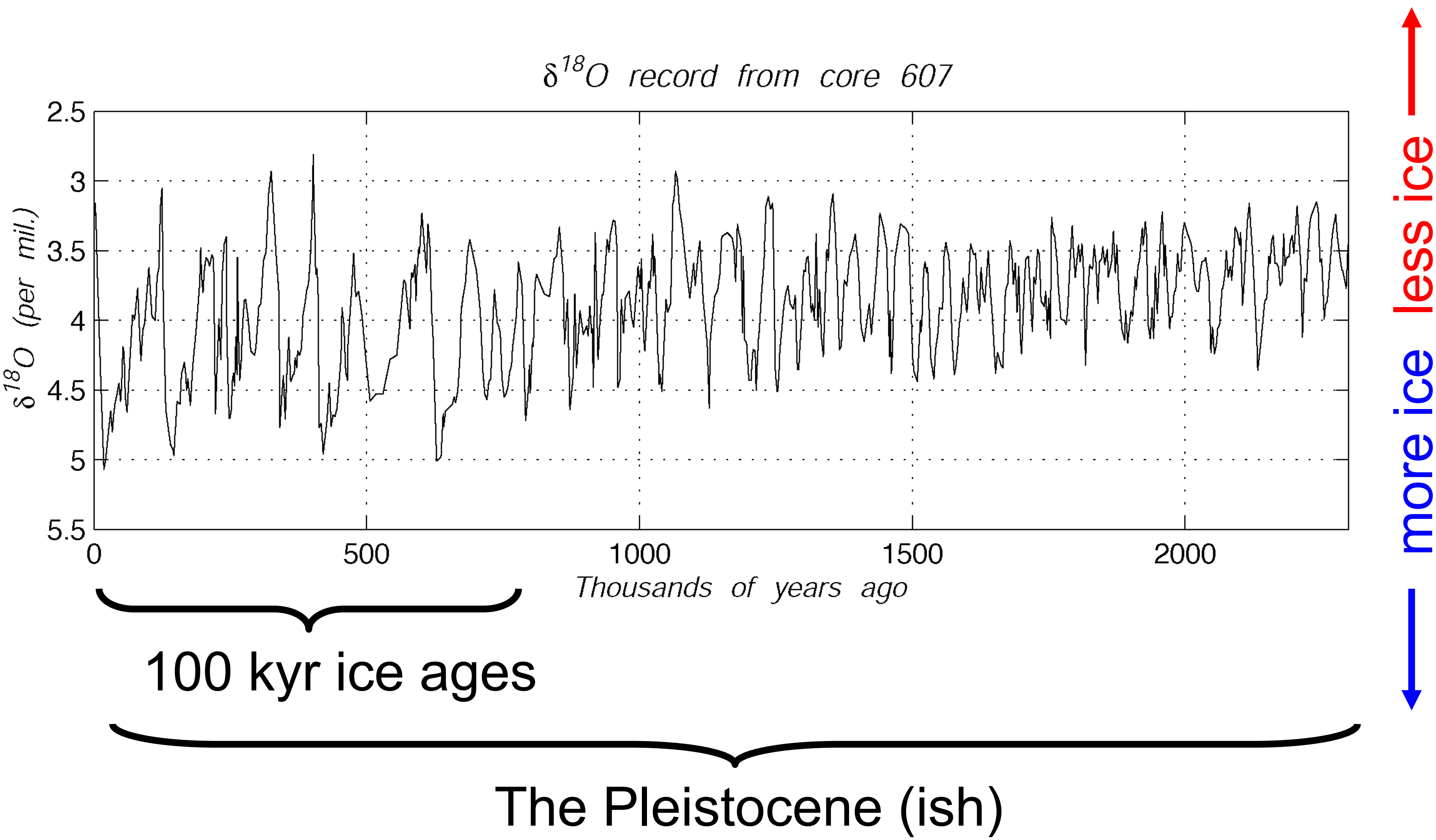
- fractionation of isotopes during evaporation and precipitation favours light isotopes being transported to high latitudes.

- ocean becomes enriched in heavy isotopes.

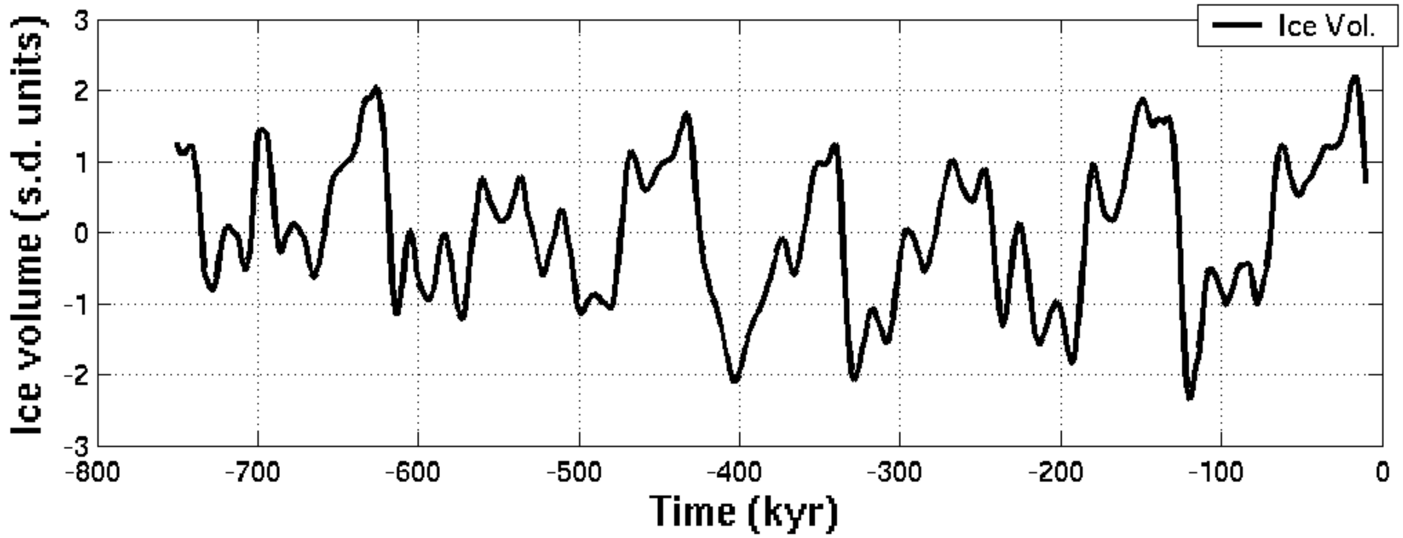
- signal can be measured in ocean sediments.

Inferring global ice volume in the past

• proxy for ice volume over the last 2.5 million years



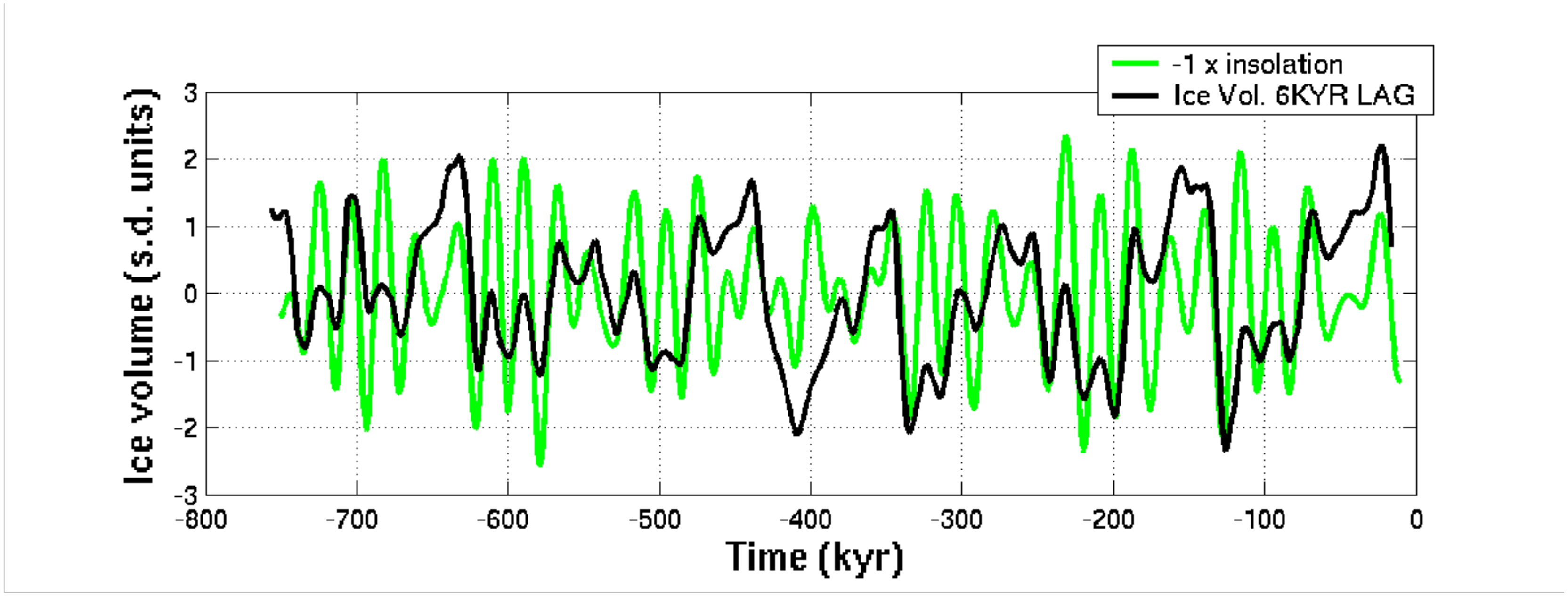
The SPECMAP ice volume time series



- Composite stack of many $\delta^{18}O$ deep sea cores (~20)

Imbrie et al., 1984

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

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

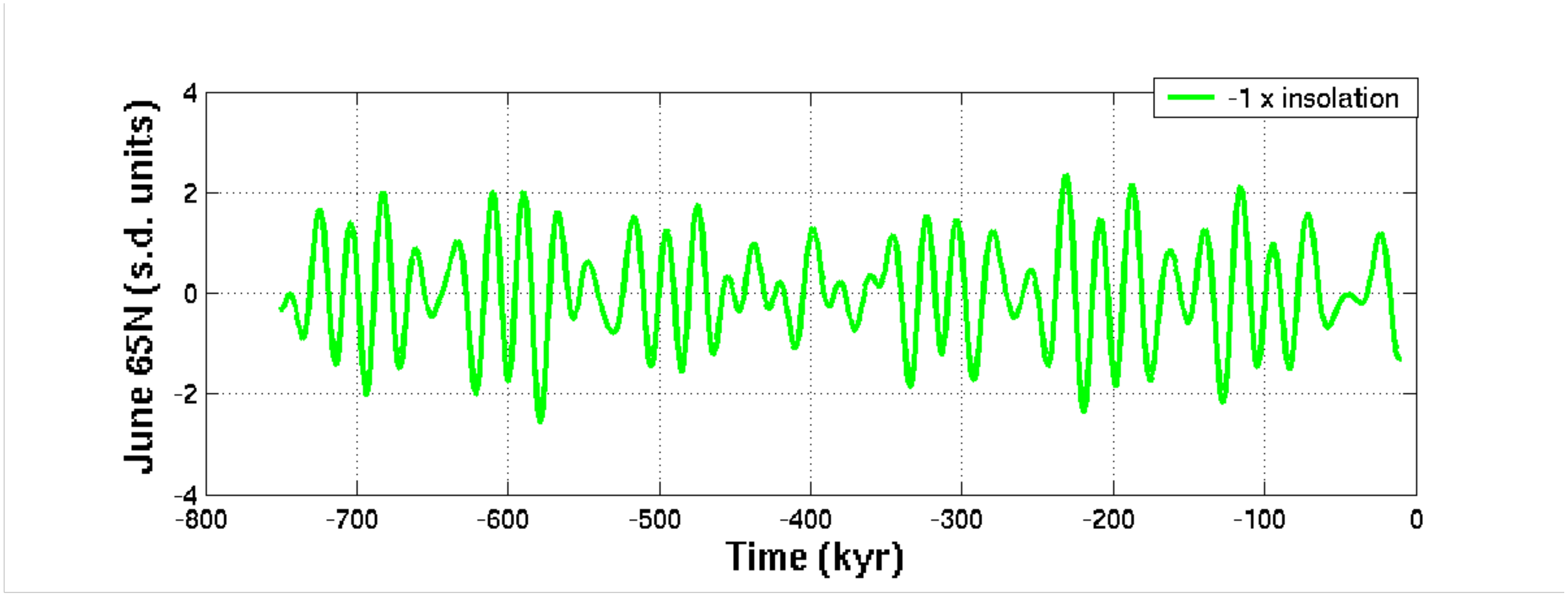
• S.H. temperatures lead ice volume by ~6 kyr
=> S.H. source of deglaciation mechanism

• 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…

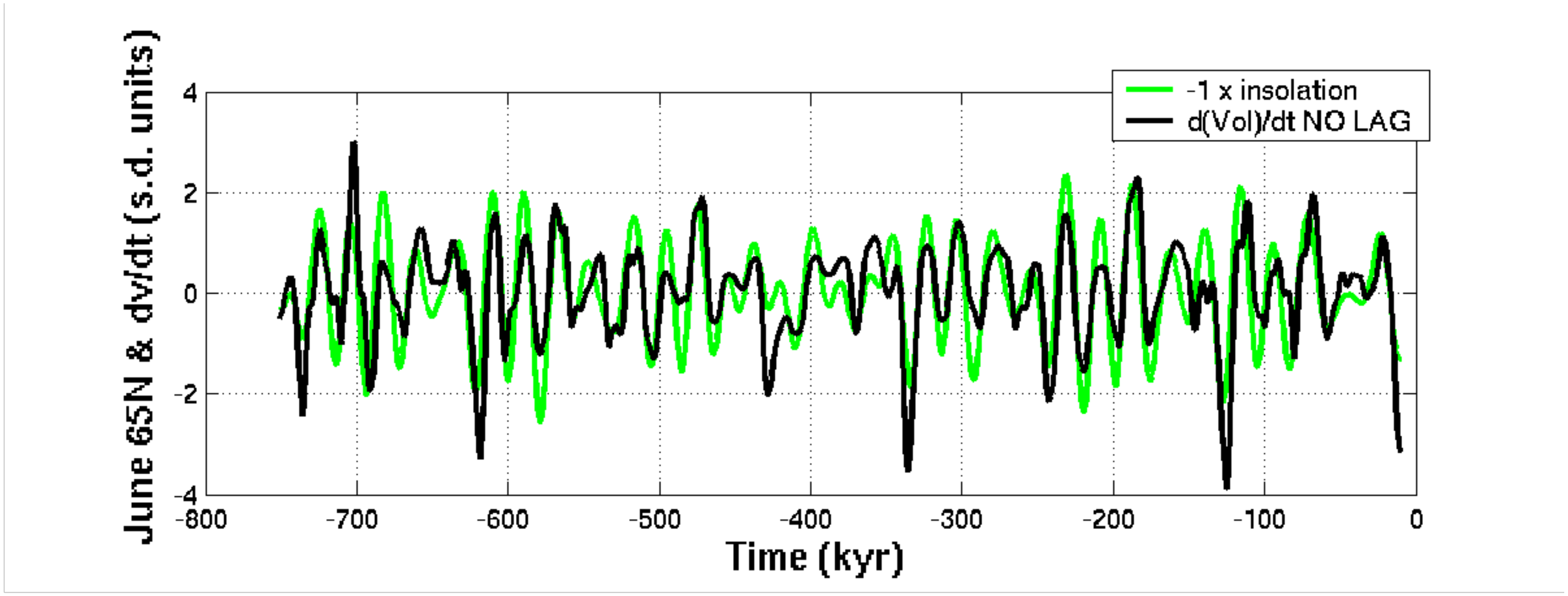
Rate of change of ice volume

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



Rate of change of ice volume

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

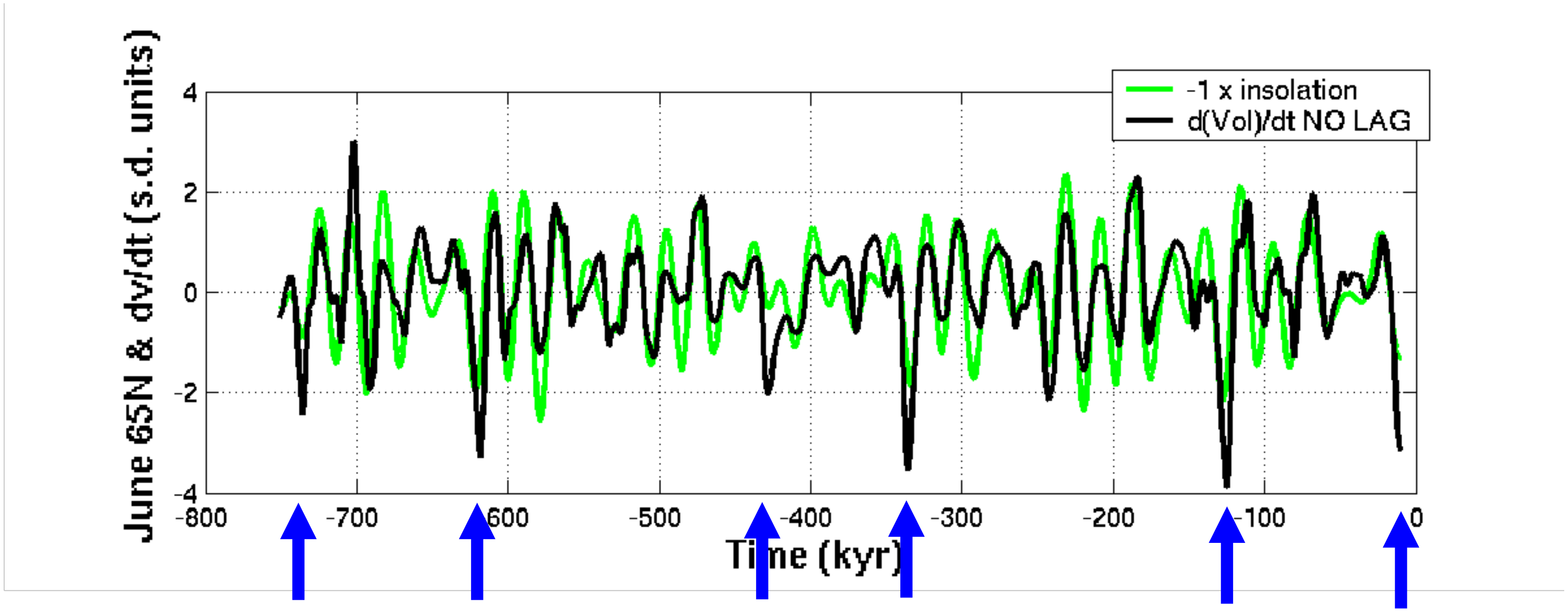


• **maximum correlation of -0.8**

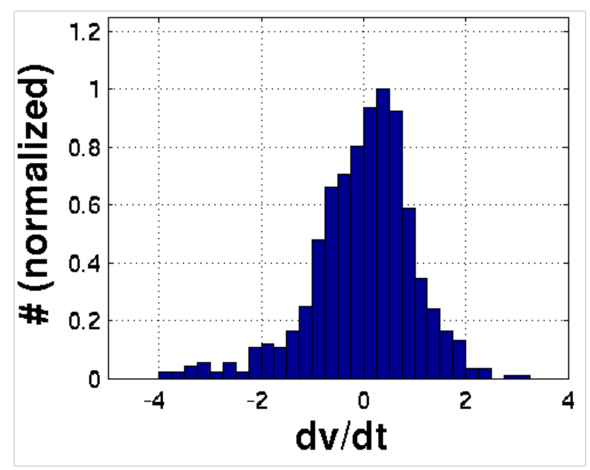
at zero lag

Rate of change of ice volume

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

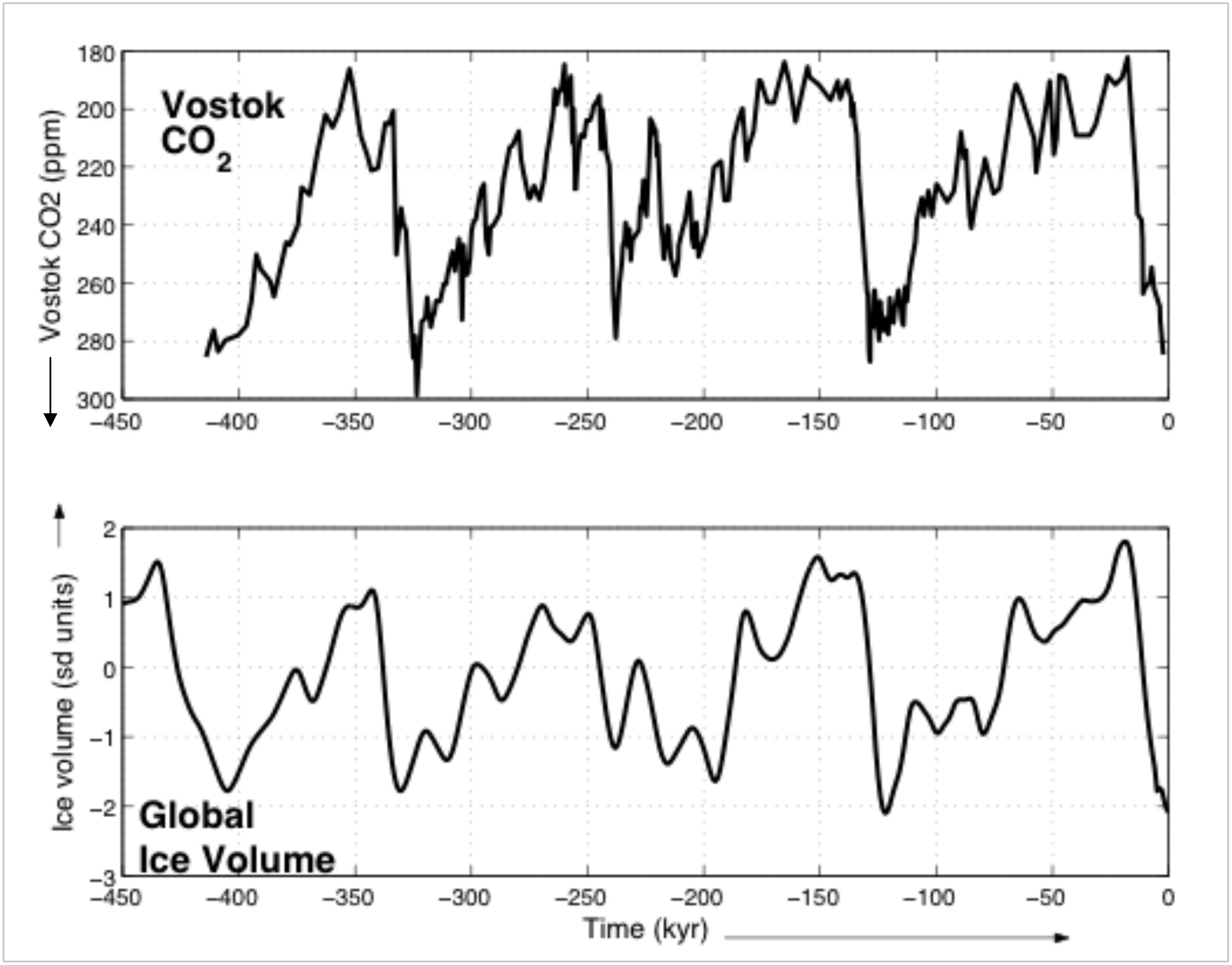


• major difference is large negative rates of change during major deglaciations



• Terminations coincide with insolation maxima - points to insolation trigger

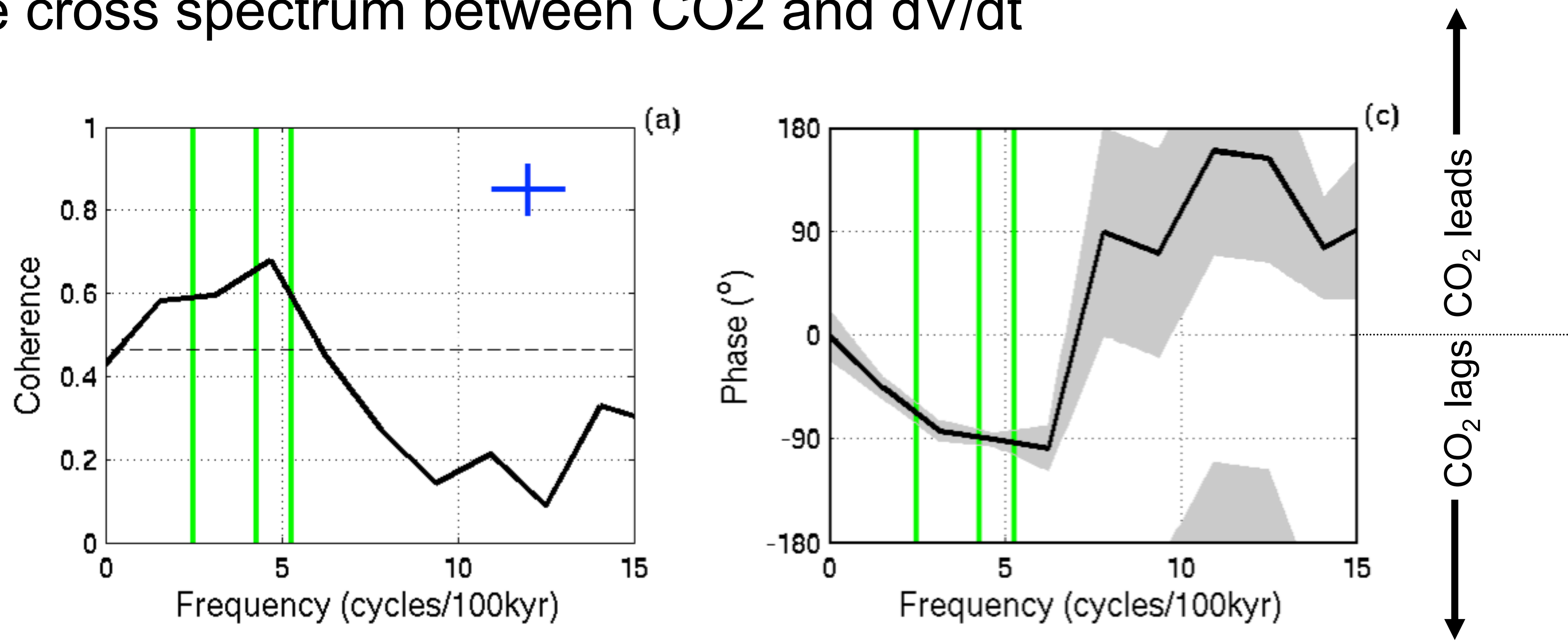
The role of CO_2:



Changes in CO_2 lead changes in ice volume…

The role of CO_2:

The cross spectrum between CO2 and dV/dt



• Variations in melting *precede* variations in CO_2!

Summary

- Waxing and waning of global ice volume strongly controlled by high latitude, northern hemisphere summertime insolation

  (i.e., Milankovitch's original idea, sort of)

- CO_2, tropical SSTs lag dV/dt - not the primary driver of variations

- Insolation trigger for collapse?

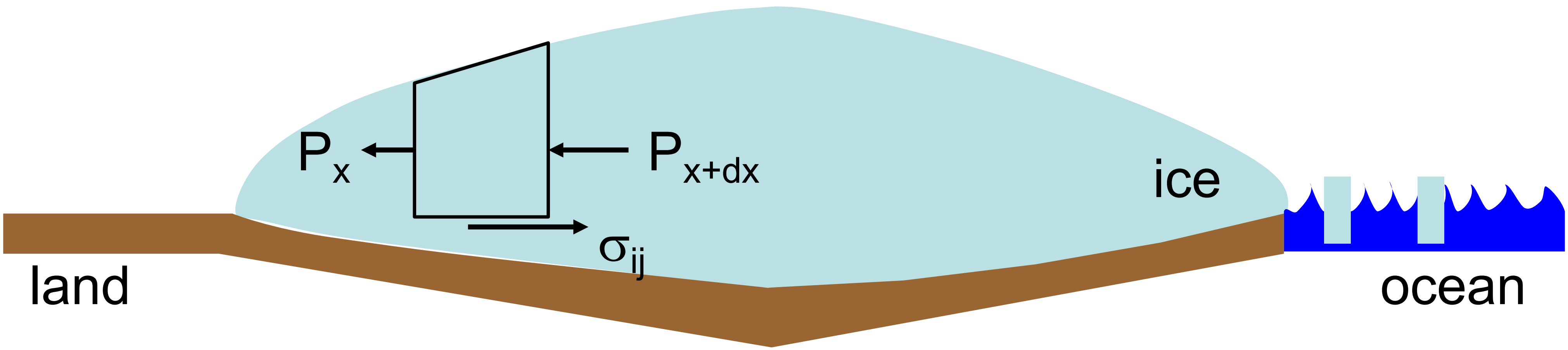
- Reason for deglaciation still unknown

- Changes the question from does orbital forcing affect global ice volume (it does), to what causes the big deglaciations?

How an ice sheet works (roughly):

1. Force balance on a volume within ice sheet

   Surface slope leads to pressure gradient

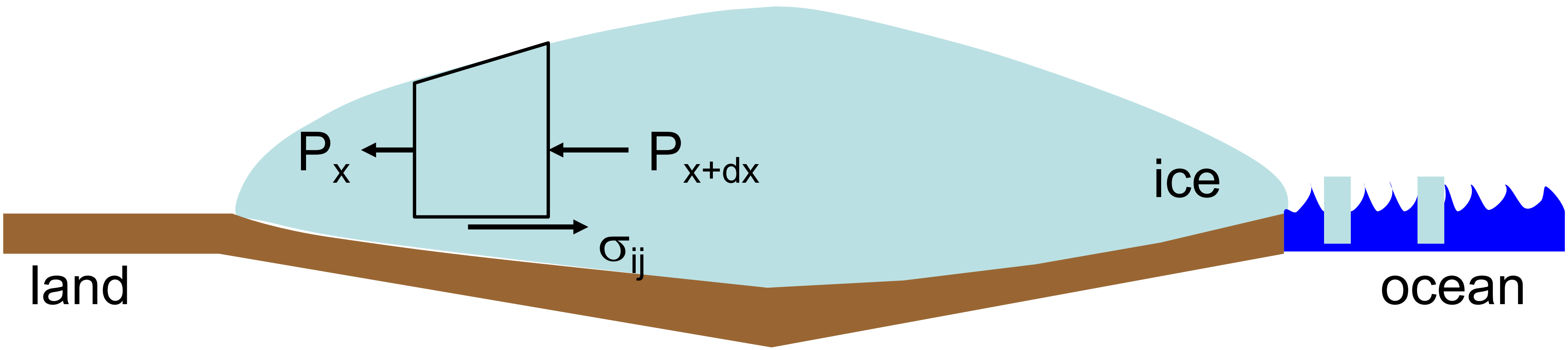


Pressure gradient balances shear stress:

$$\boxed{\sigma_{ij} = -\int_{z}^{z_s} \frac{\partial p}{\partial x} dz}$$

How an ice sheet works (roughly):

2. Ice responds to stress by **deforming** (creep flow)



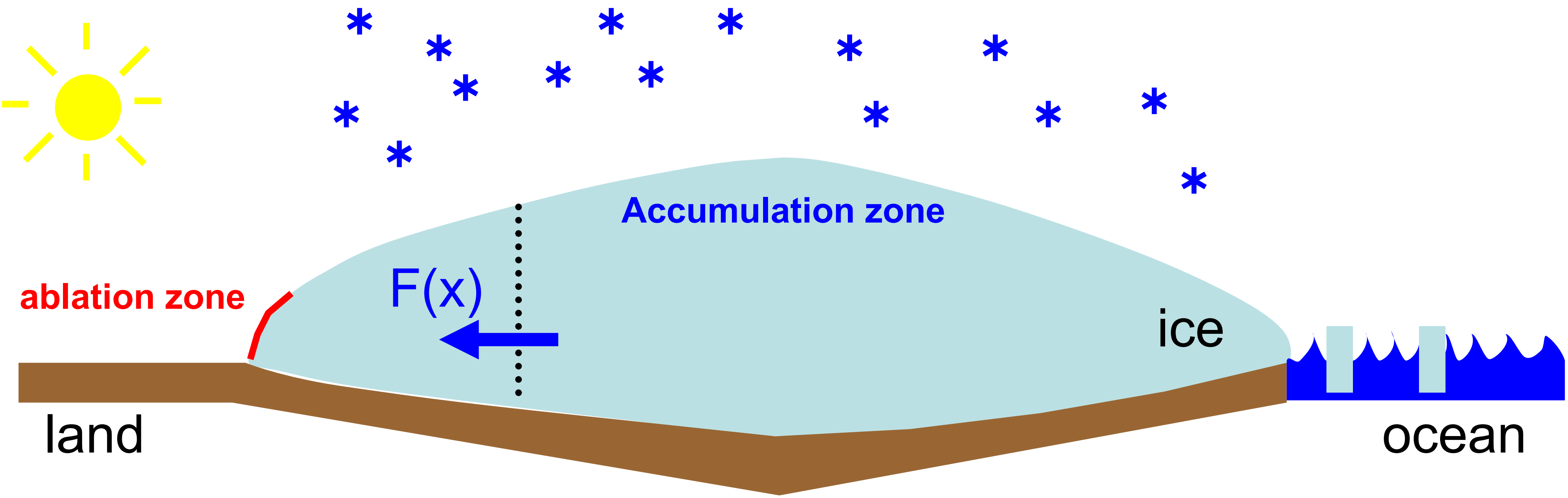
Glen's flow law: relates strain rate to applied stress

$$\dot{\varepsilon}\ (\sim \frac{du}{dz}) = A(T) \times \sigma^3{}_{ij}$$

Strain rate $\propto$ $(\text{Stress})^3$

How an ice sheet works (roughly):

3. Equilibrium state is a **flux balance**



Steady state mass balance:

$$\boxed{Flux\ of\ ice \propto H^5 \times \left(\frac{dh_s}{dx}\right)^3 = \int_0^x (snowfall - melting)\, dx}$$

- ice flow is basically a very nonlinear diffusion equation

Accumulation

Greenland - average accumulation ~30 cm/year.

Antarctica - average accumulation ~10 cm/year.

(desert <25 cm/yr)

Clausius-Clapeyron relationship:

- moisture content decreases exponentially with height.
- e-folding scale height at high latitudes ~ 2 km.
- most of Antarctica, Greenland are above this height.

As ice sheet grows, average snowfall decreases strongly

→ **strong negative feedback as ice sheet grows**

Ohmura et al., 1996

Greenland

Ablation
vs.
Summer temperature

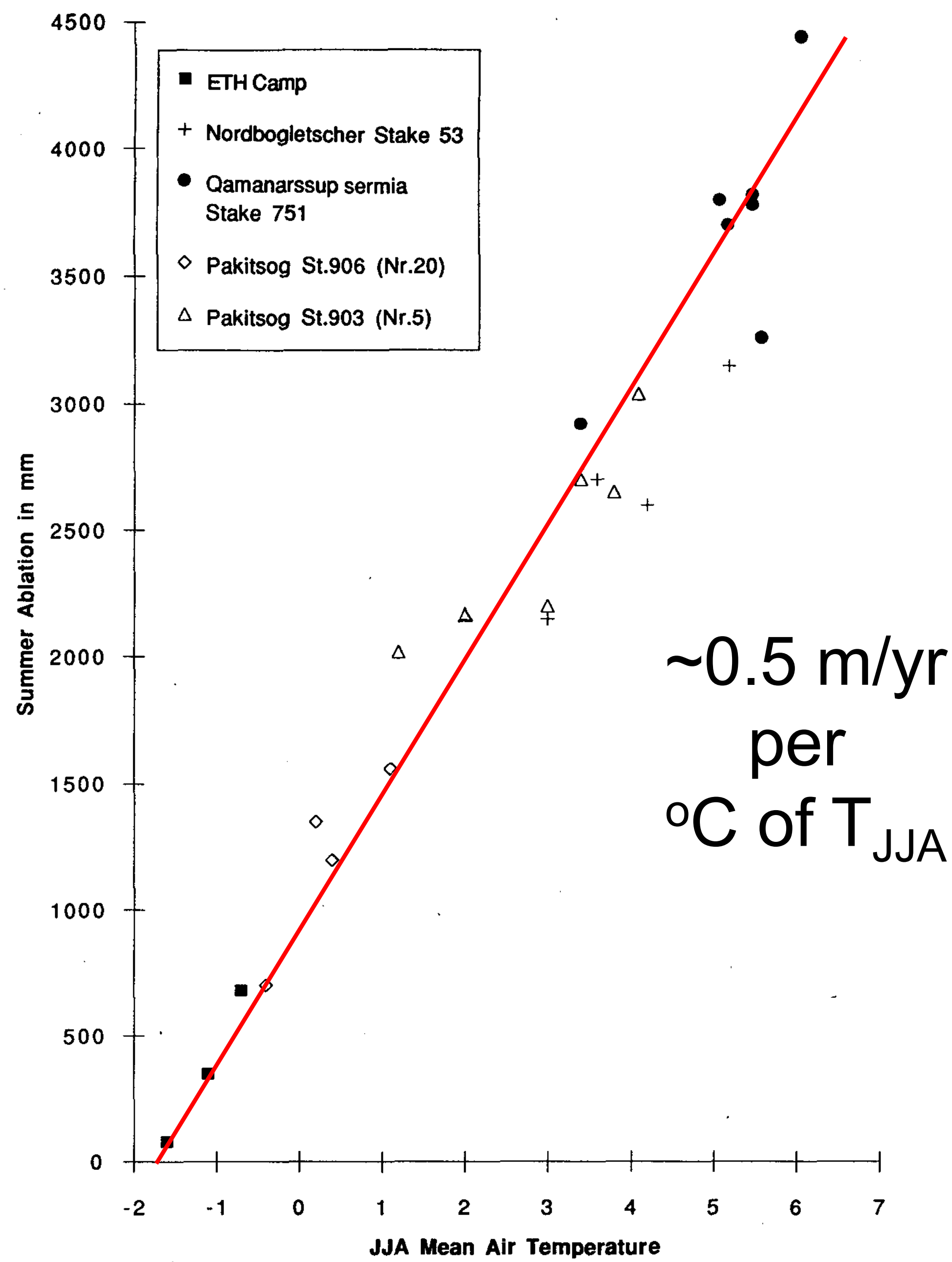
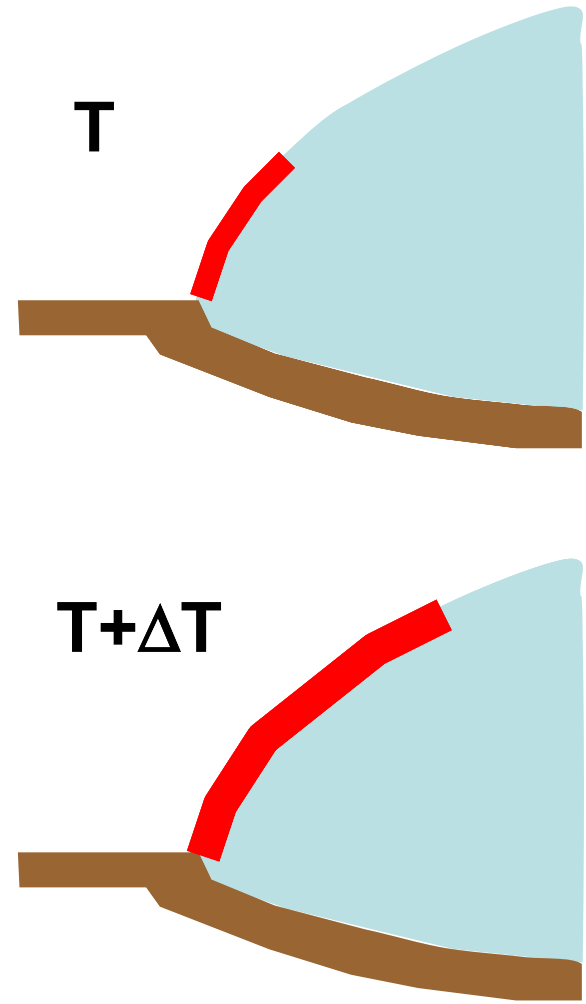


FIG. 9. Relationship between the annual total mass loss due to ablation and mean air temperature for June, July, and August for Greenland. Note that −2°C is the minimum required temperature for the mass loss.

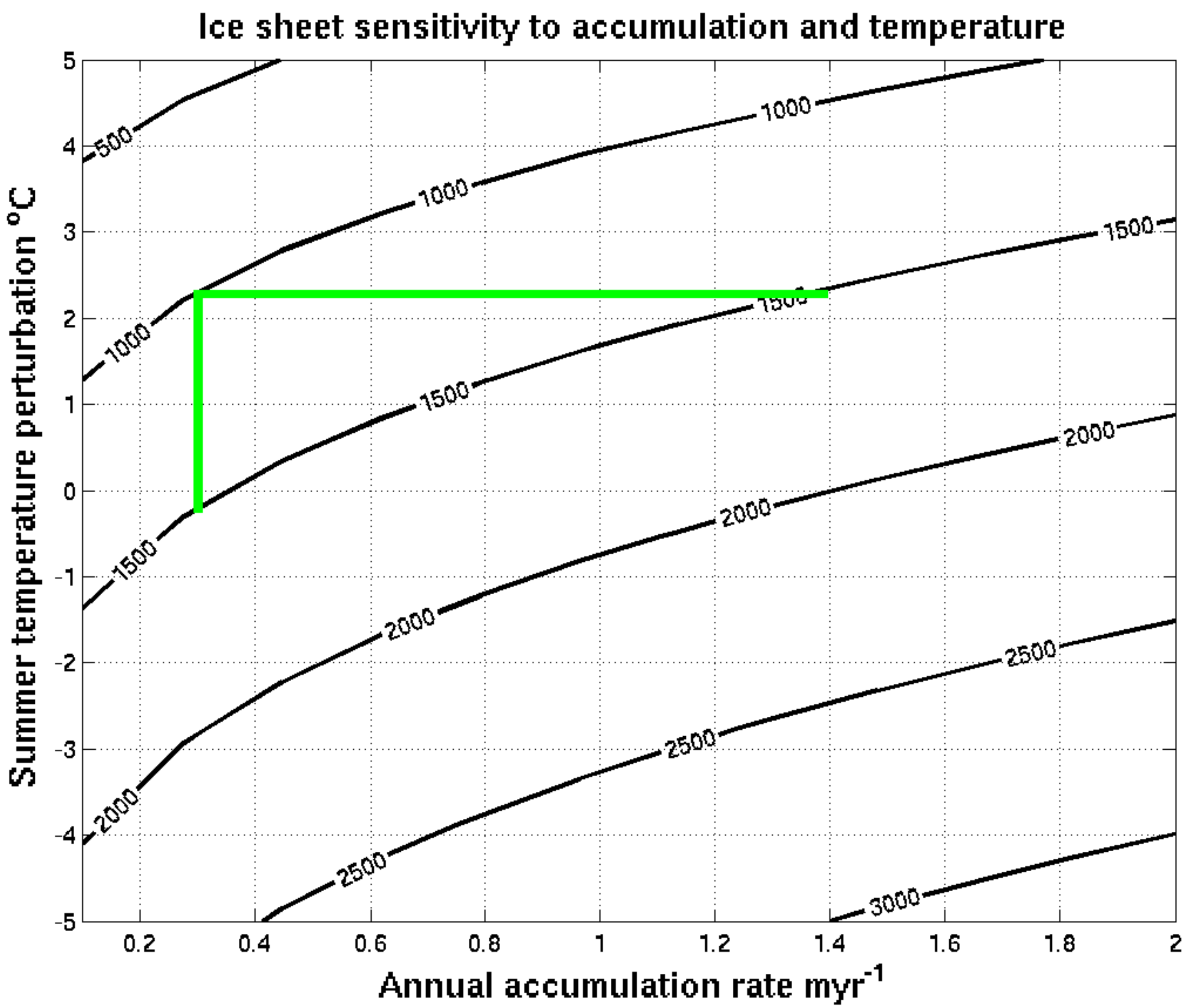
Ablation



- Ablation rate $\propto$ summer temperature.
- Rule of thumb 1°C JJA $\cong$ 1myr^{-1} melting.
- Ice sheet margin has parabolic shape.
- **Total ablation $\propto$ T^3.**

Ice sheets are very sensitive to summertime temperatures!

Ice sheet sensitivity: accumulation rate vs. ablation rate



Contours of ice sheet length (in km)

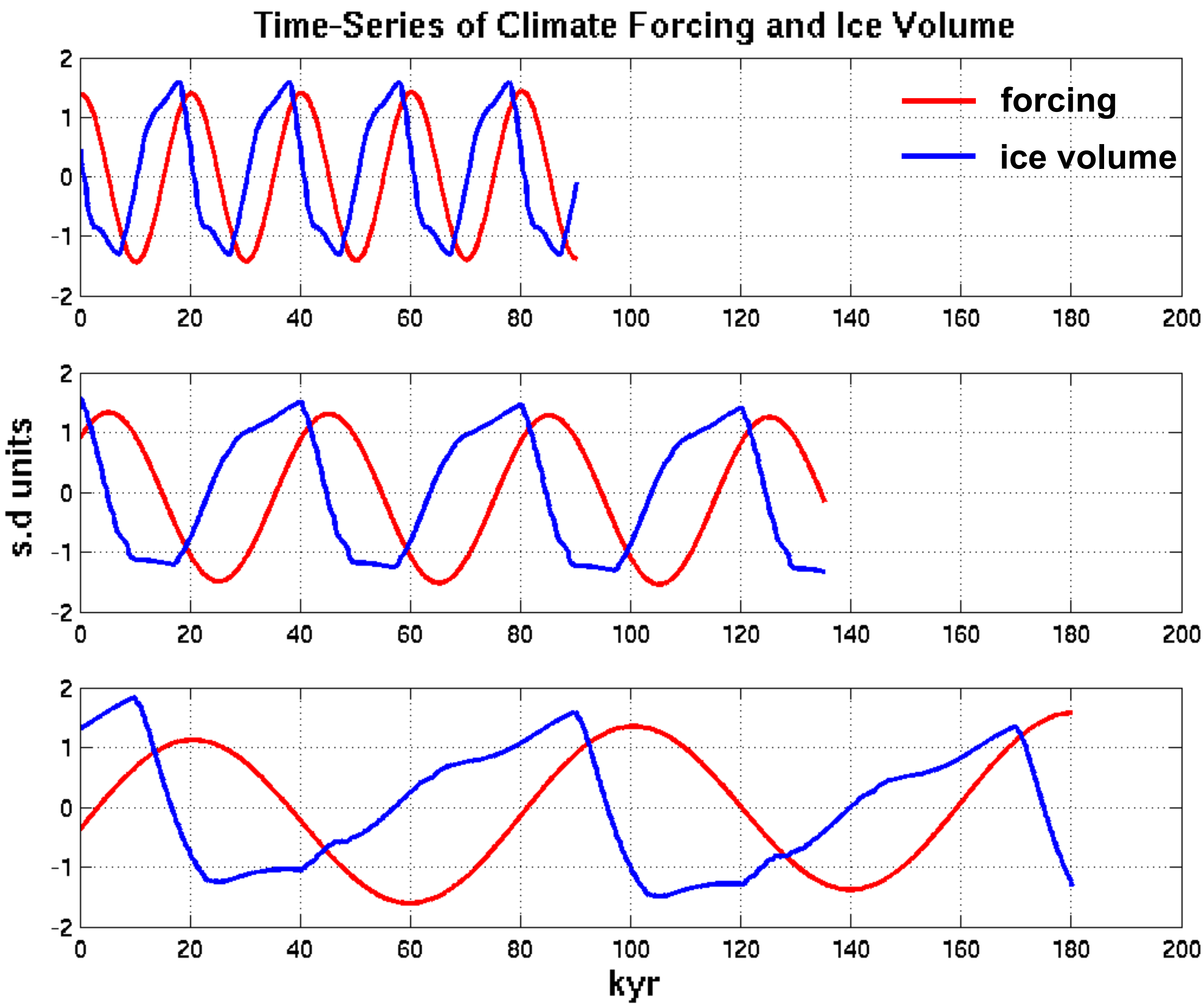
- **need a big accumulation rate change to offset a small temperature change.**

Ice volume response for different forcing periods

20 kyr

40 kyr

100 kyr

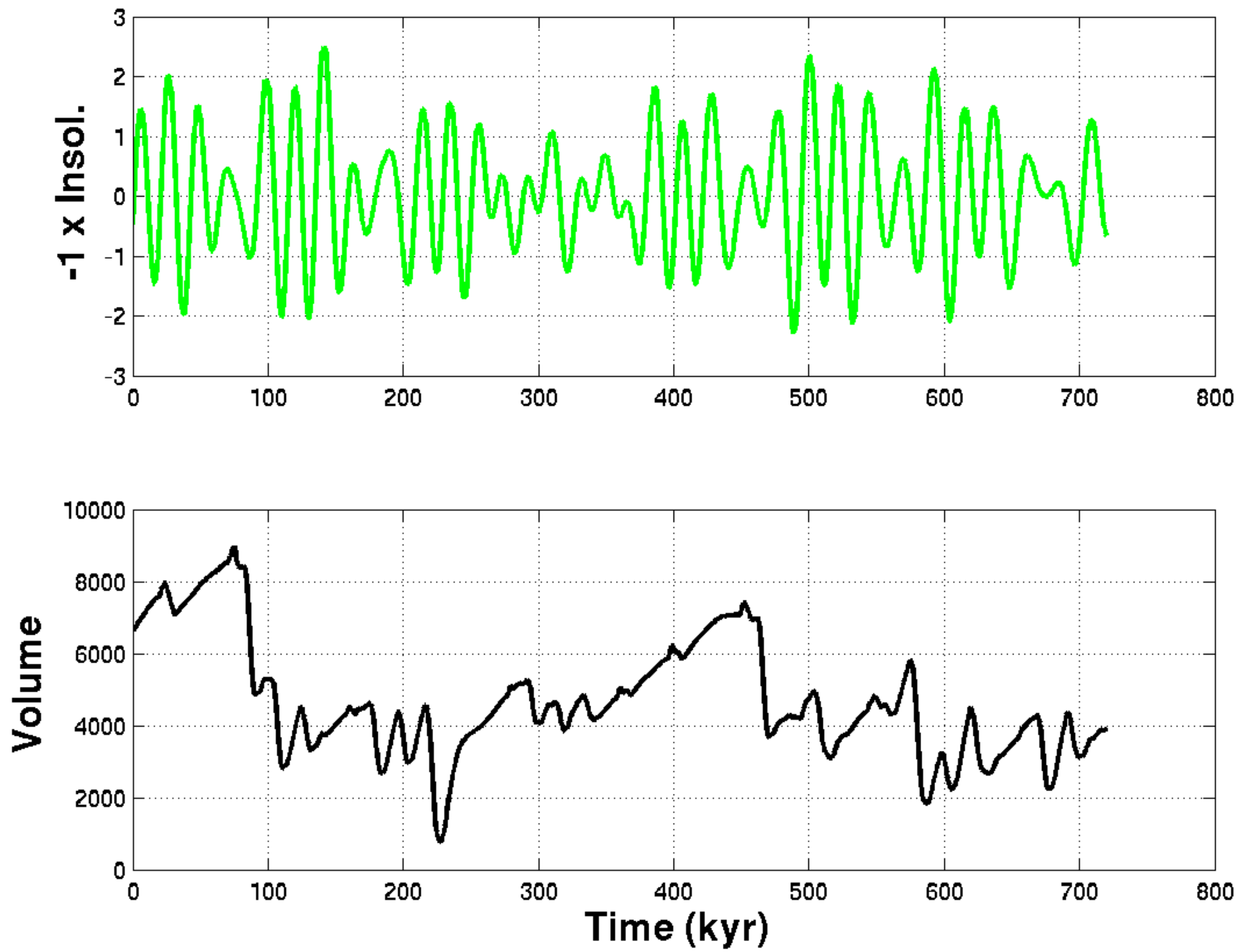


Use insolation variations to force ice sheet model

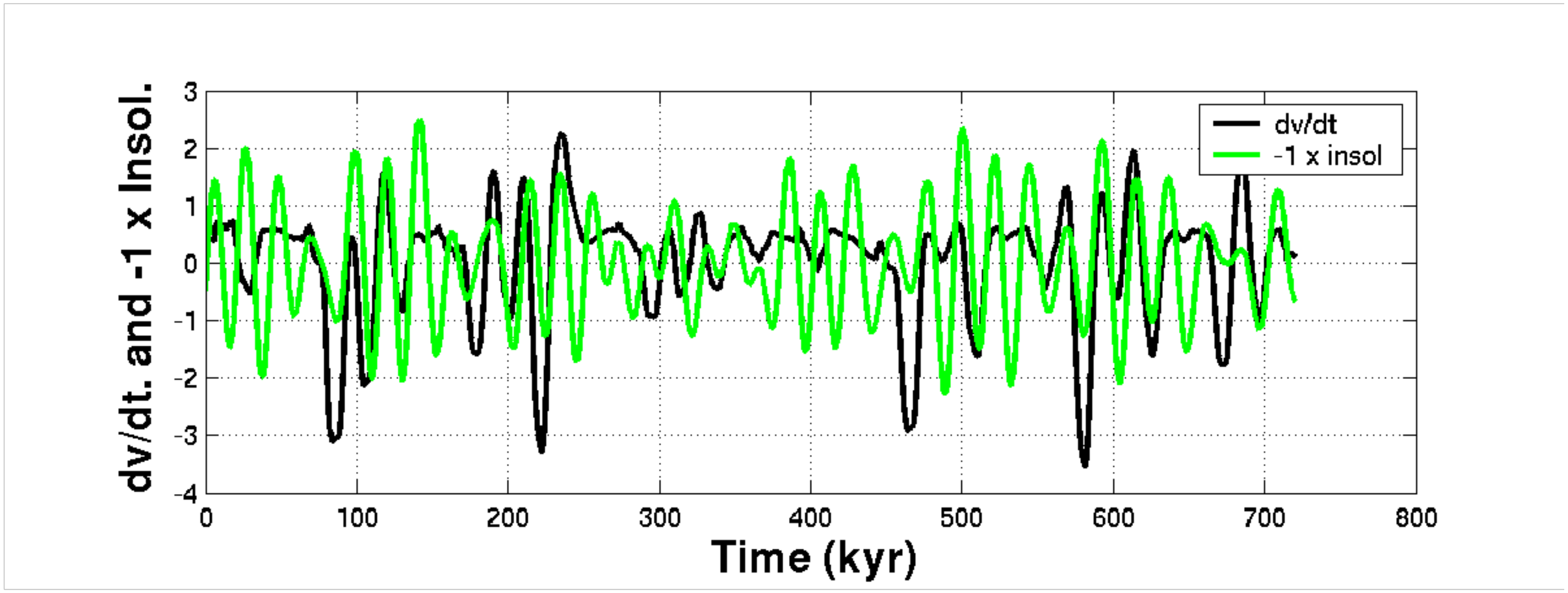
Forcing

=

response



Comparison of model dv/dt with model forcing



- maximum correlation 0.4

  at zero lag

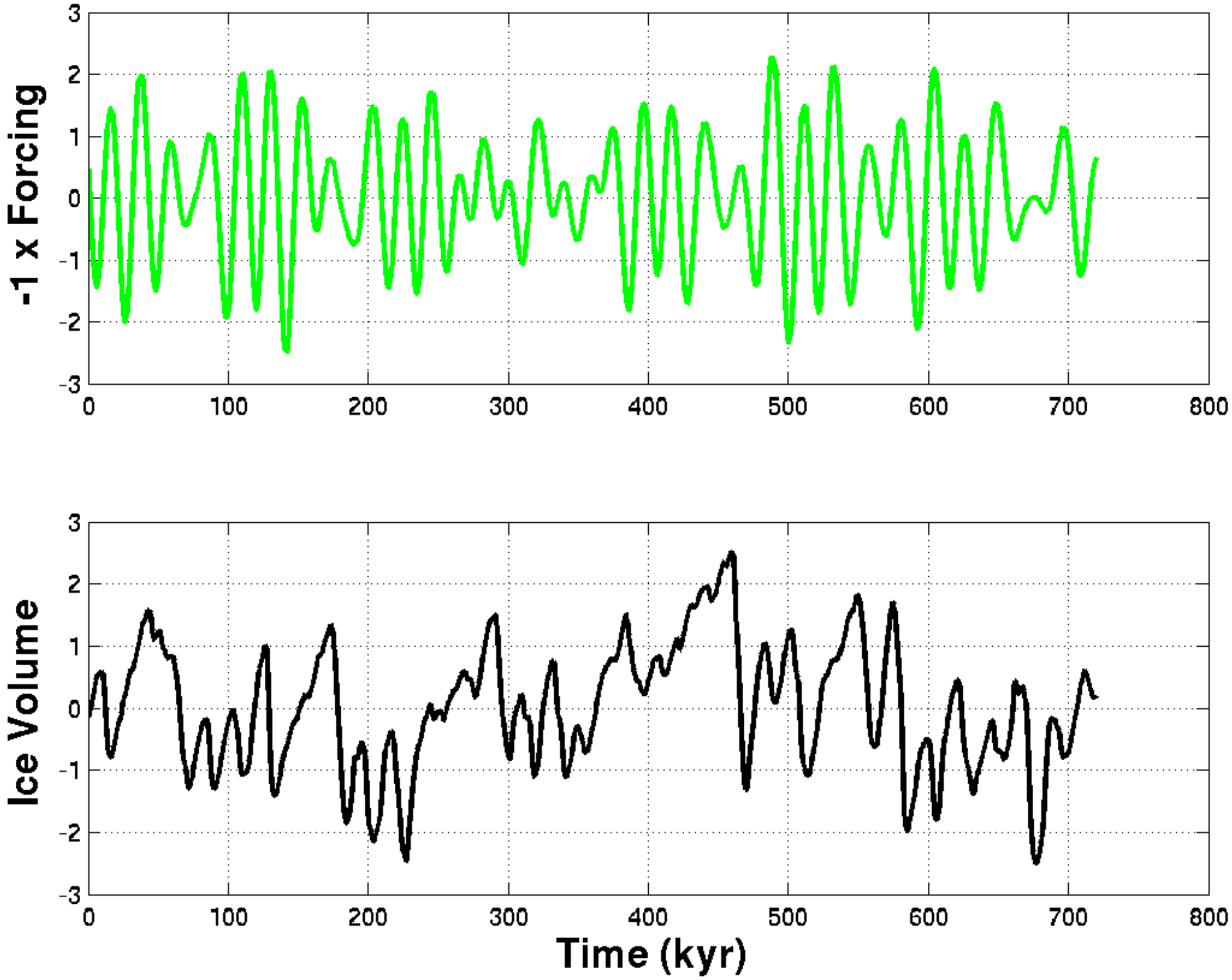
Use insolation variations to force ice sheet model

plus noise

Forcing
(plus
white noise)

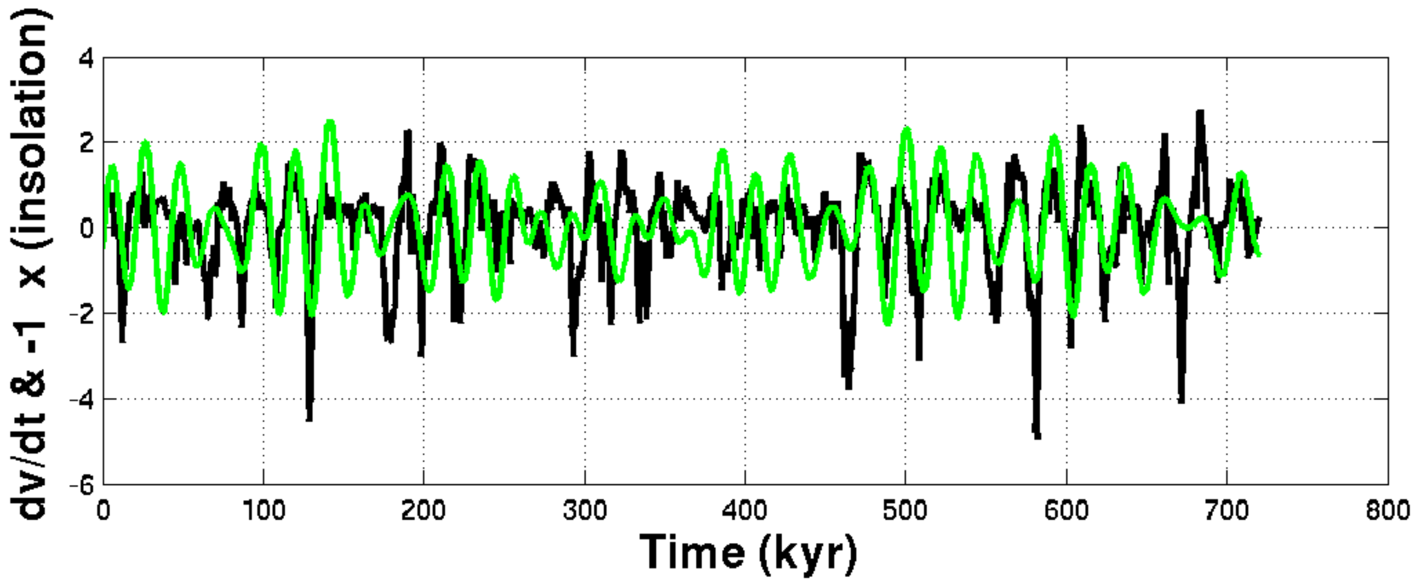
=

response



Comparison of model dv/dt with model forcing

plus noise



- maximum correlation 0.35

  at zero lag

Conclusions

- Models and observations agree that rate of change of ice volume
  is directly related to insolation variations.
  (up to 60% of variance)

- The Milankovitch hypothesis (formulated properly) does,
  in fact, explain a lot about climate change, but noise
  is an important part too.

- Ice sheets are very nonlinear beasts.

- How do large ice sheets collapse?