Climate forcings and feedbacks

The 100 kyr glacial cycles

Plan for Today:

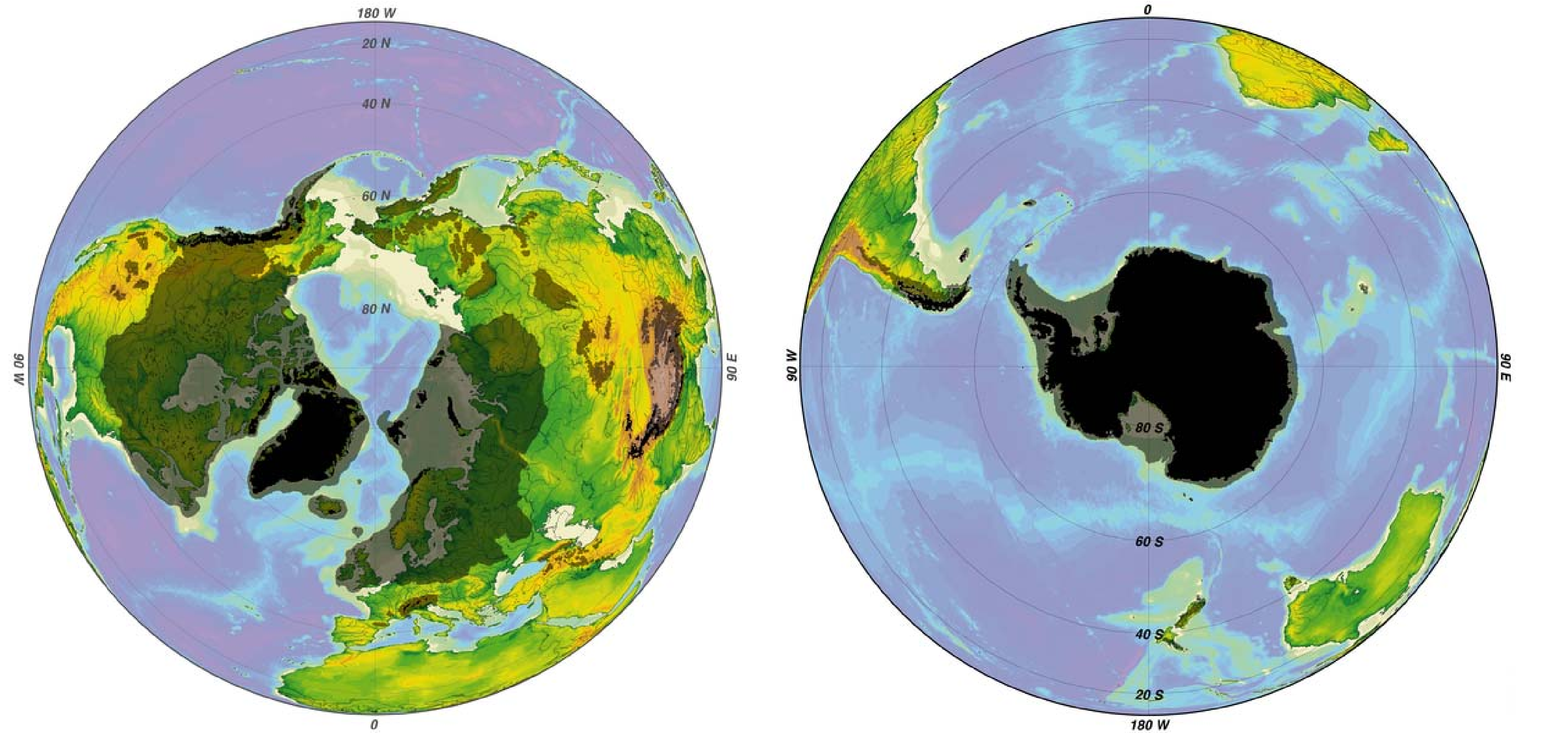
9.15-11: Lecture: Forcings and feedbacks over glacial cycles.

- Evidence of glacial cycles
- Insolation forcings and the 100kyr glacial cycle

11-12: Exercises

- Finish exercises and discuss results

What we know: Growth of Northern Hemisphere ice sheets during glacials.



Land ice at present vs. at last glacial maximum (20 kyrs before present)

The history of ice ages

How do we know climate has changed?

Proxy data:

Geological evidence (moraines, deposits)

Oxygen isotopes (ice cores and ocean cores)

Drift deposits, including glacial sediments at top and bottom of the section, with fluvial and lake deposits in between.

Drift deposits in coastal cliff at Glanllynau, Lleyn Peninsula, North Wales. Photo M. J. Hambrey.

Fluted moraine: A set of low ridges formed parallel to ice flow, metre-scale in width, 100 metre-scale in length. They commonly extend down-valley from a boulder, and consist of till.

Fluted lateral moraine near Austre Lovénbreen, Svalbard. Photo M. Hambrey.

Natural abundancy of stable isotopes of water

$$H_2{}^{16}O \quad : \quad HD^{16}O \quad : \quad H_2{}^{18}O$$

$$997680 \quad : \quad 320 \quad : \quad 2000$$

(in ppm)

The isotopic composition of water is given by the relative deviation from a standard (SMOW=Standard Mean Ocean Water):

$$\delta = \frac{R_{prøve} - R_{SMOW}}{R_{SMOW}} \cdot 1000 ‰$$

EKS :

$$\delta^{18}O \qquad R = \frac{[{}^{18}O]}{[{}^{16}O]}$$

$$\delta D \qquad R = \frac{[D]}{[H]}$$

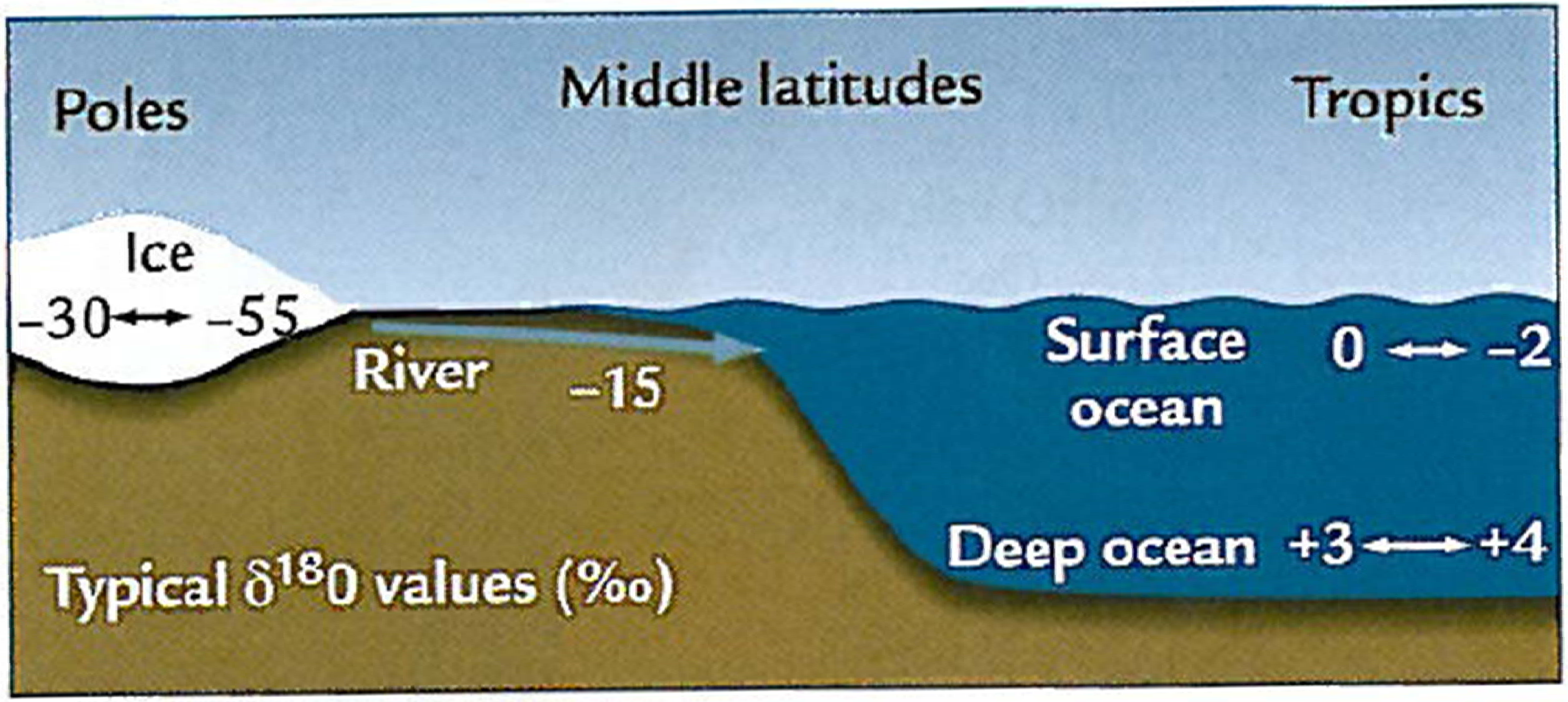


FIGURE 1 $\delta^{18}O$ values in the modern world In the modern ocean, $\delta^{18}O$ values vary from 0 to −2‰ in warm, tropical surface waters to as much as +3 to +4‰ in cold, deep ocean waters. In today's ice sheets, typical $\delta^{18}O$ values reach −30‰ in Greenland and −55‰ in Antarctica.

The vapour pressure of the isotopes are different
→ Fractionation occurs during evaporation/condensation processes

The light isotopes have a higher vapour pressure (p) than the heavier isotopes (p'):

$$p(H_2{}^{16}O) > p'(H_2{}^{18}O)$$

At 20ºC:

$$\alpha = \frac{p}{p'}$$

= 1.08 (D)

= 1.009 (^{18}O)

The light isotopes are more likely to evaporates and condensates than the heavy isotopes.

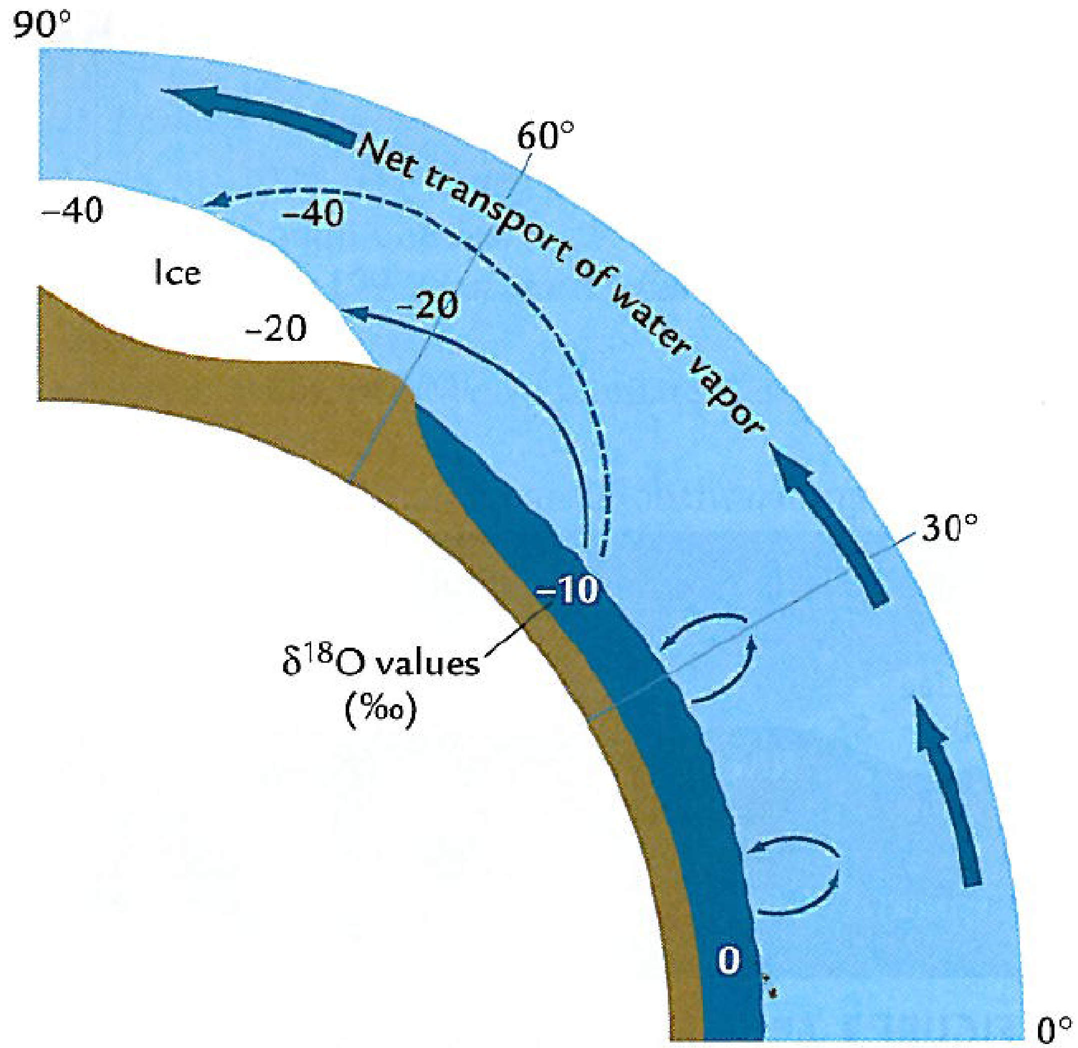
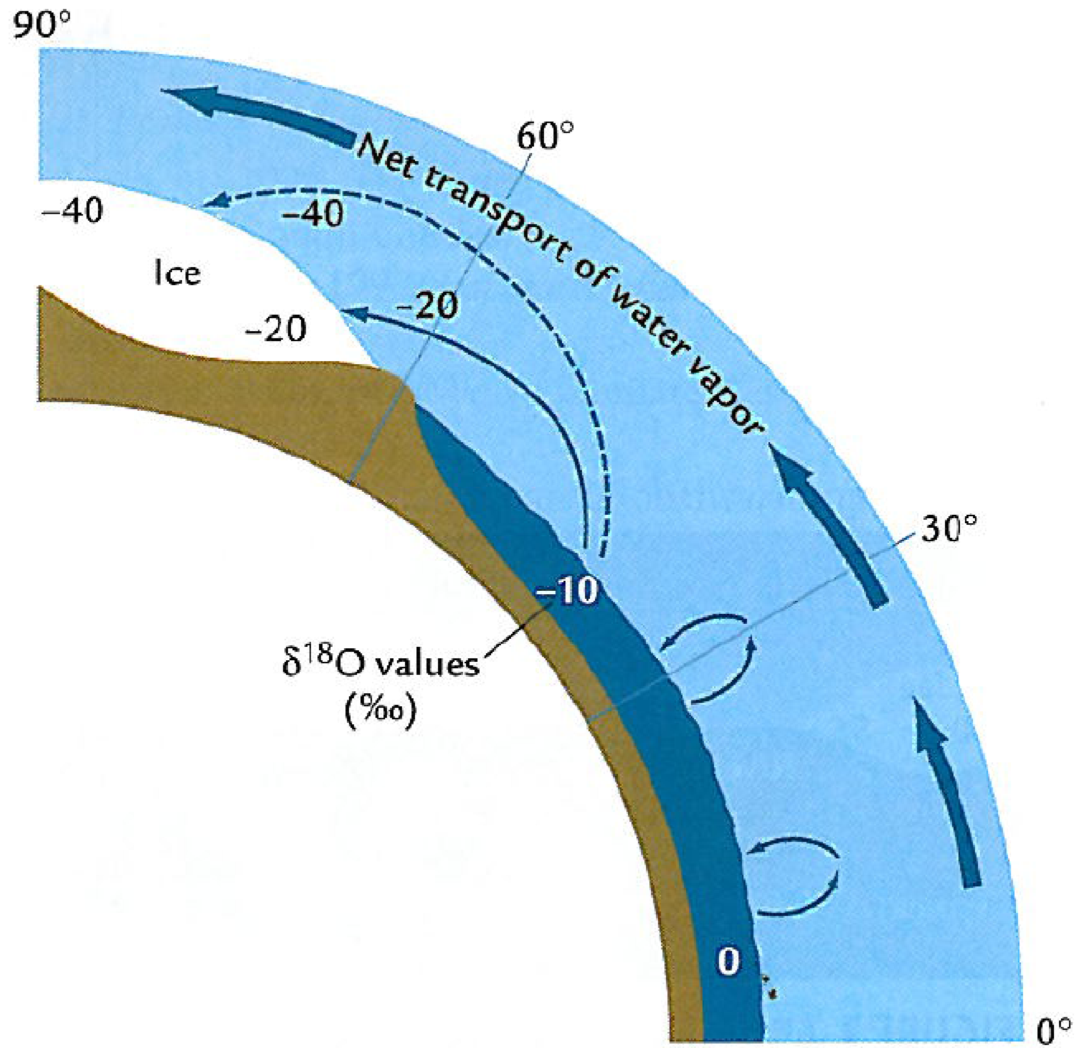


FIGURE 2 Isotope fractionation As water vapor moves from the tropics toward the poles, it is enriched in the ^{16}O isotope during each step of evaporation and condensation. This fractionation process makes the $\delta^{18}O$ values of snow falling on (and stored in) ice sheets more negative (^{16}O-rich).



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Two types of paleoclimatic archives provide proxy records based on stable water isotopes:

Ice cores from the polar ice sheets:

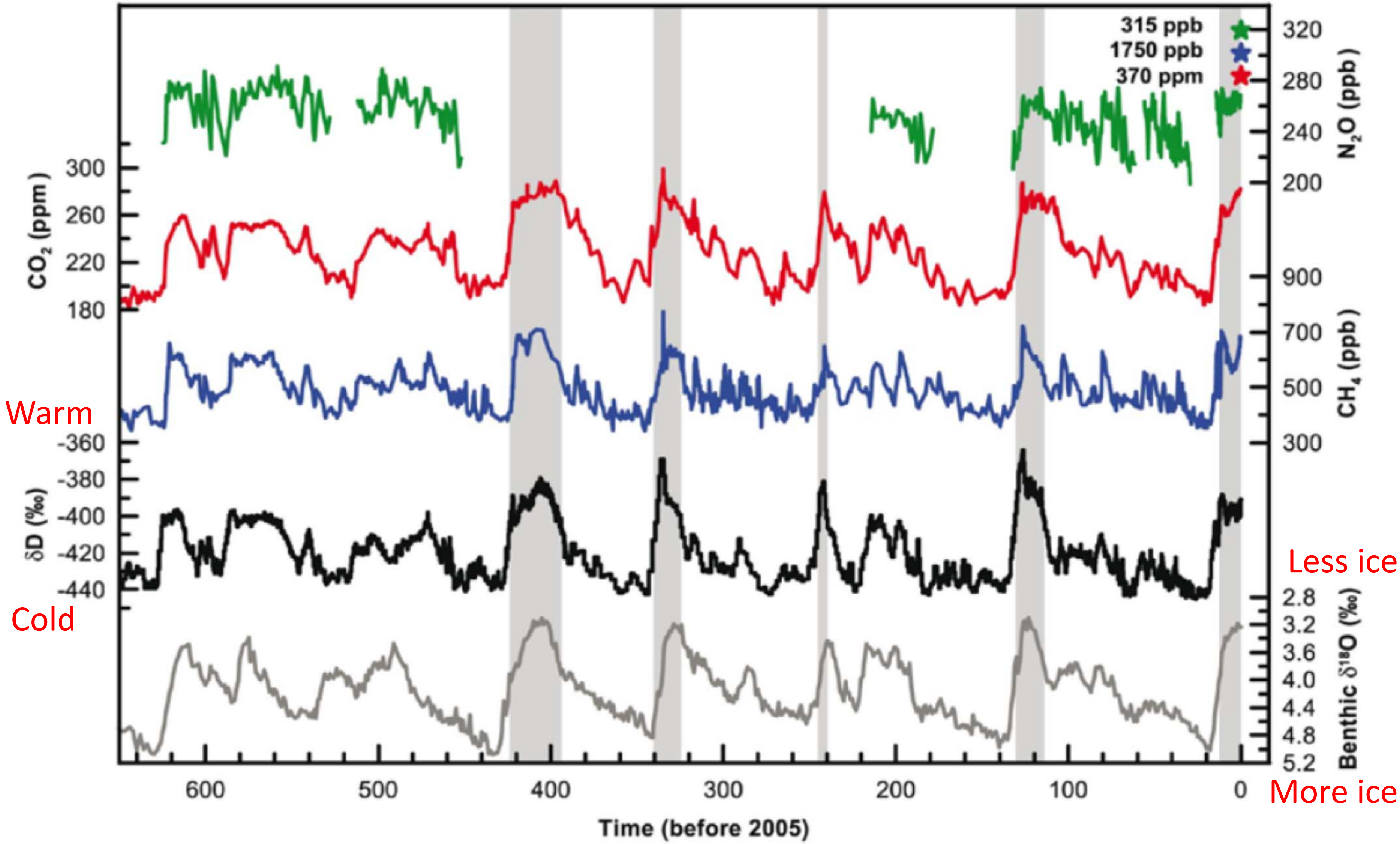
- $\delta^{18}O$ and δD records inform of the past surface temperature at the site.
- Airbubbles contain samples of the past atmosphere (CO_2, CH_4…)

Marine sediment cores from the ocean:

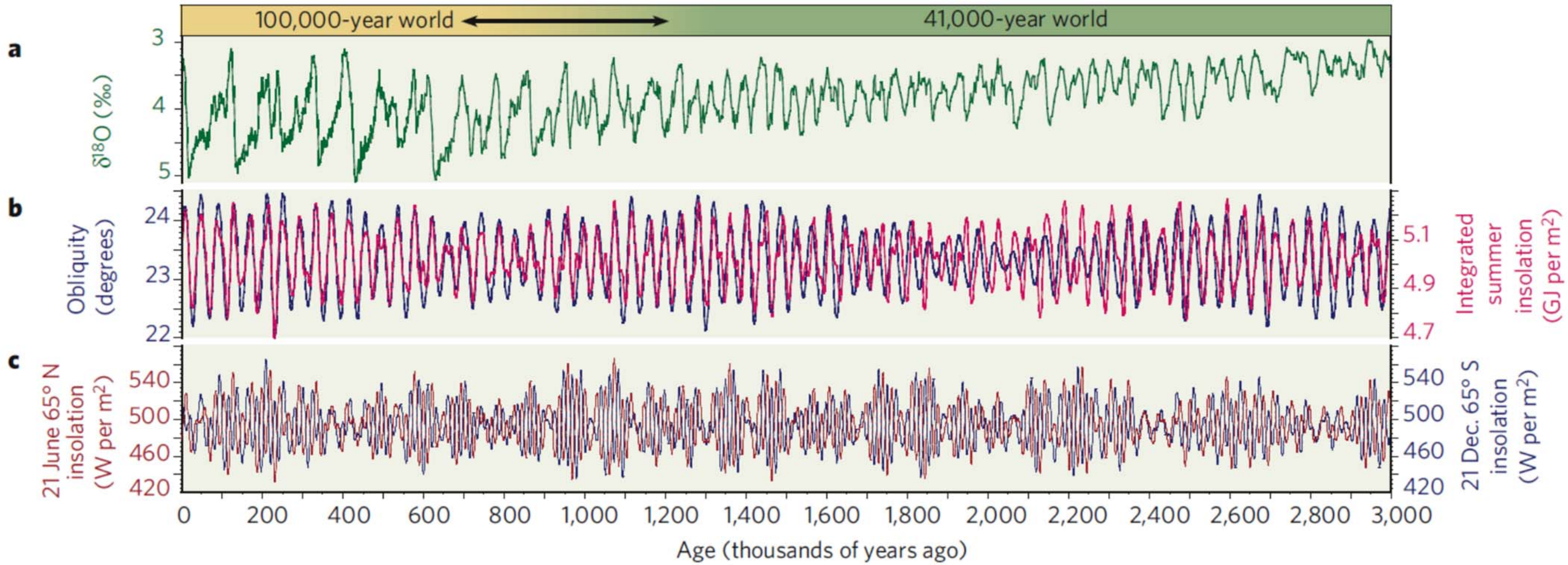
- $\delta^{18}O$ records from $CaCO_3$ inform of the past volume of land ice
- Foraminifera species inform of temperature (bottom or surface)

What are the drivers of the glacial cycles in Earth climate history ?

- **Forcings and feedbacks**



What we know: the volume of continental ice through > 5 Myr:
tells a story of ice age cycles (100kyr, 40kyr) and a general trend of build-up of ice.
Ice sheets build-up slowly, but retreat quickly.



Raymo and Huybers (2008)

Support of the Milankovitch theory:

- Ice volume varies at frequencies predicted by orbital forcing.

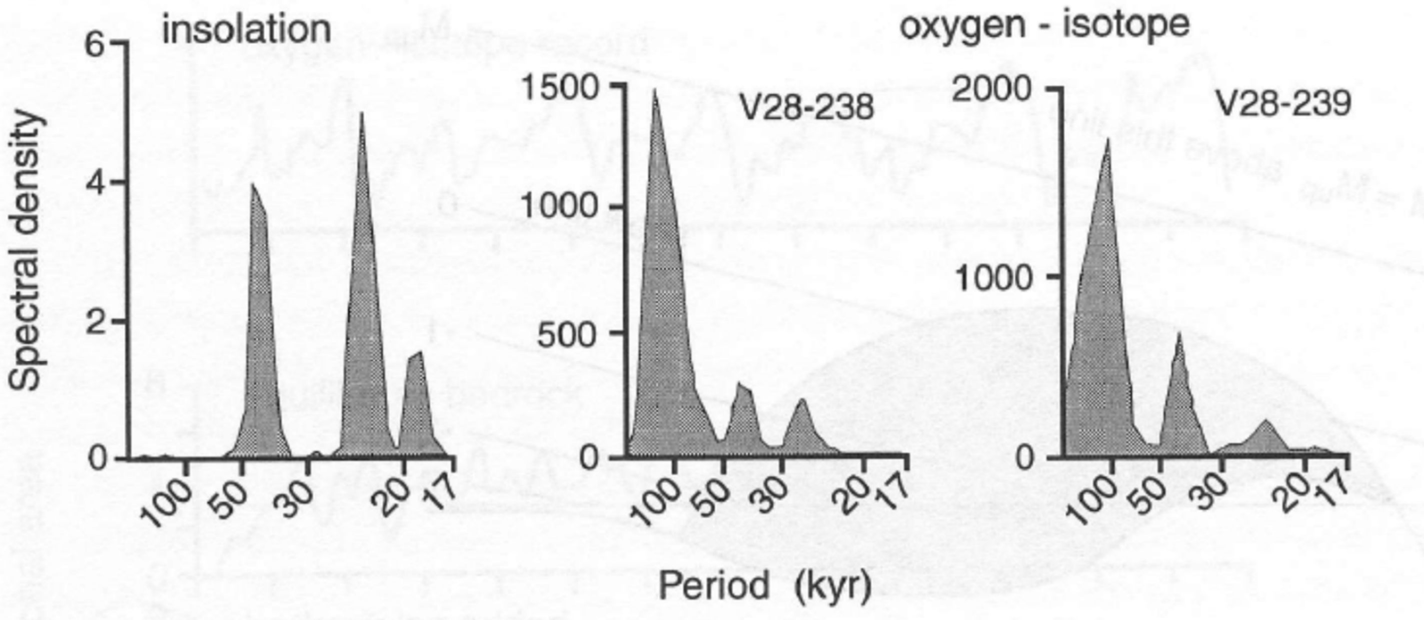


Figure 9.22. Power spectrum of the insolation time series of Berger (1978b) and of the $\delta^{18}O$ time series of two deep sea cores (from: Peltier 1982; Birchfield et al. 1981).

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Unresolved issues:

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- Why are the 100kyr cycle so strong in climate records?
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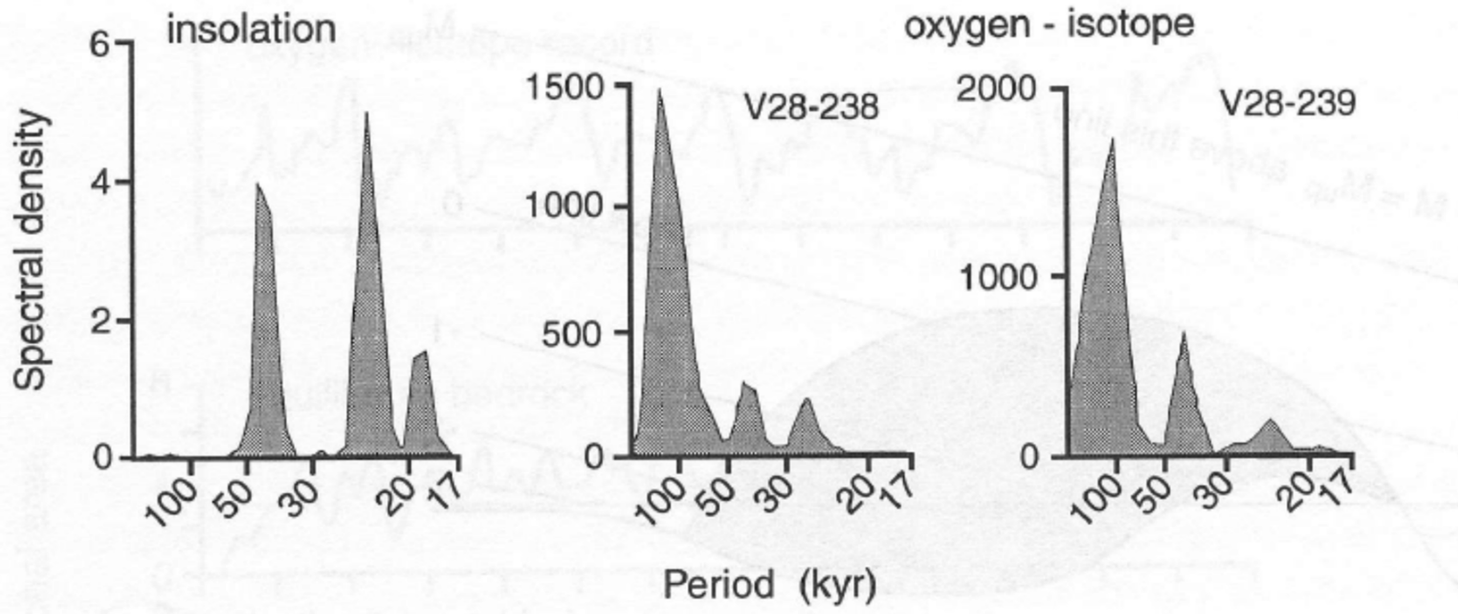
- Why is there no precession cycle in climate records from >1Myr?



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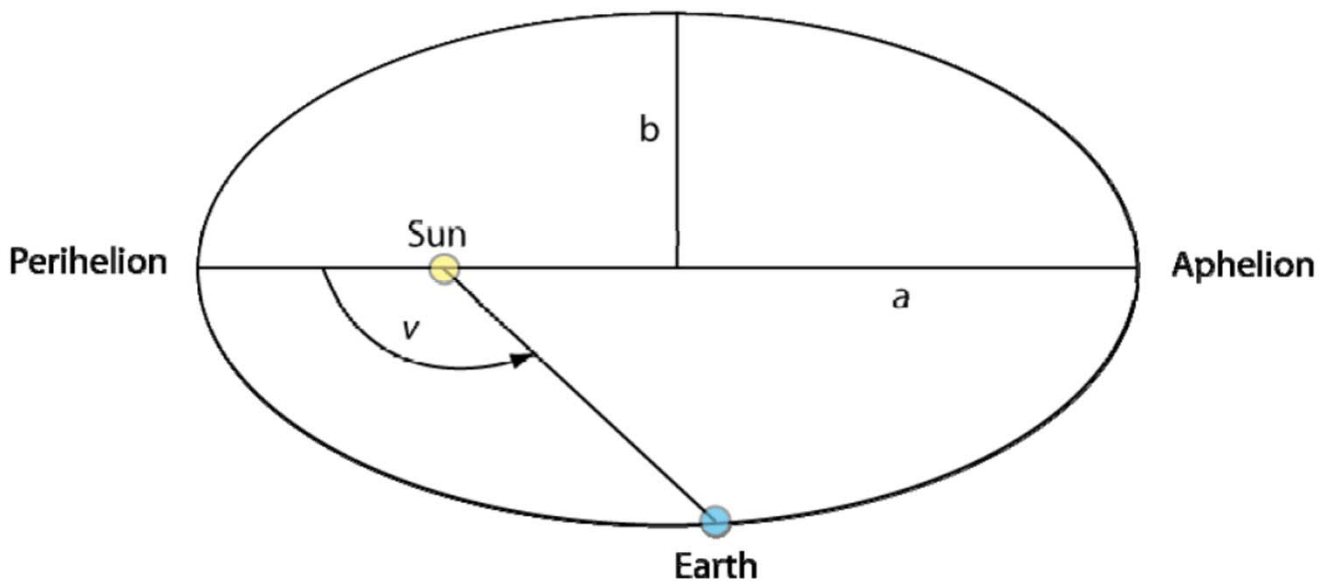
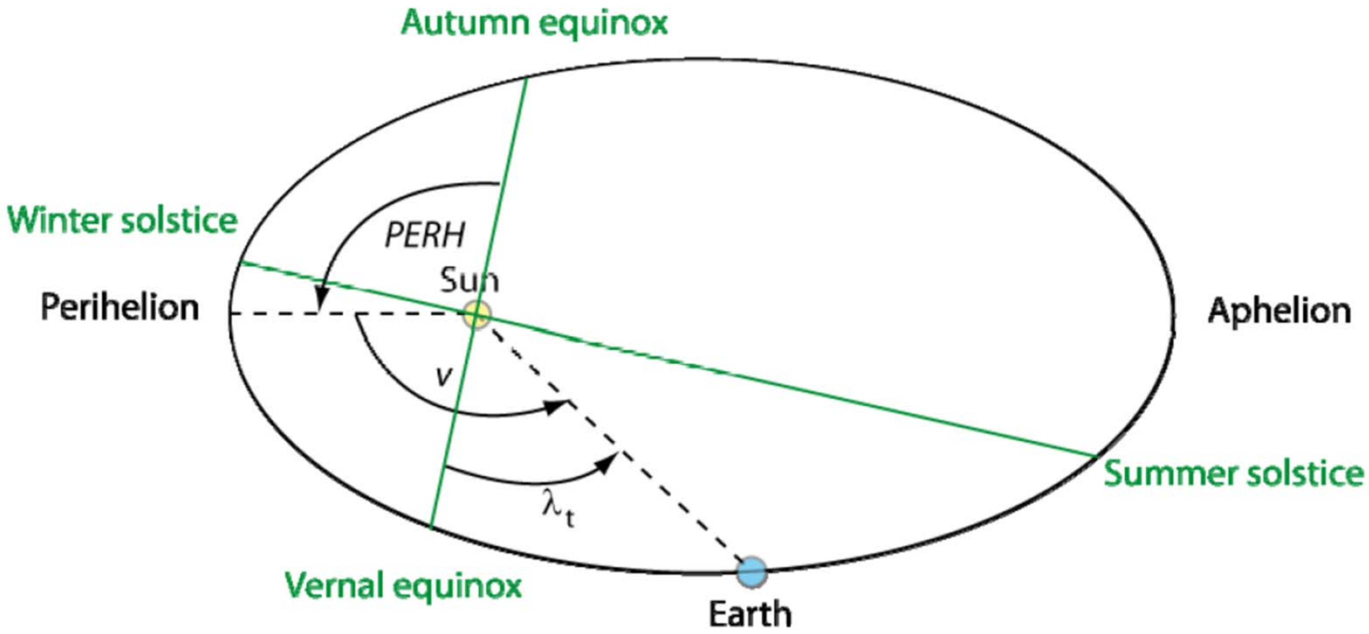
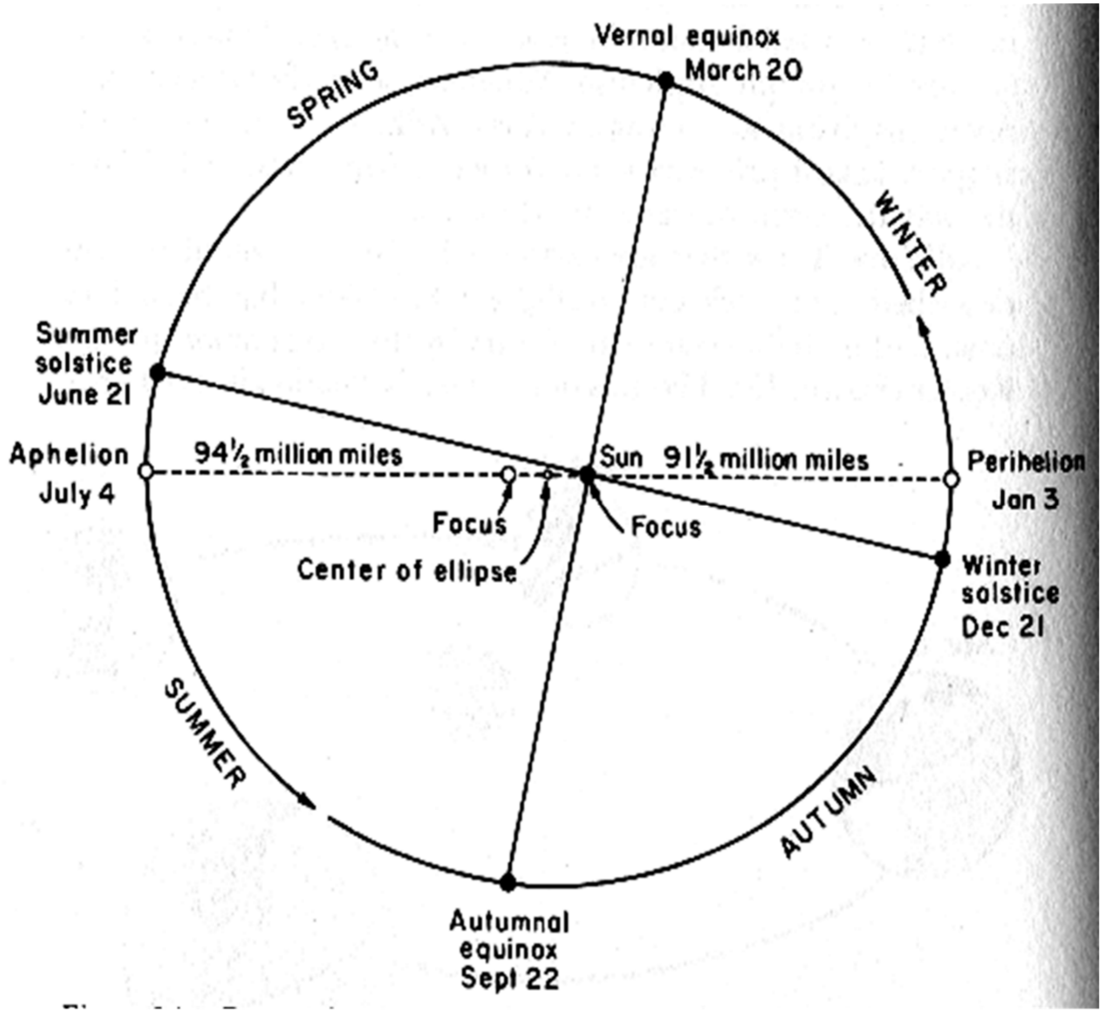
Earth orbit and the seasonal cycle



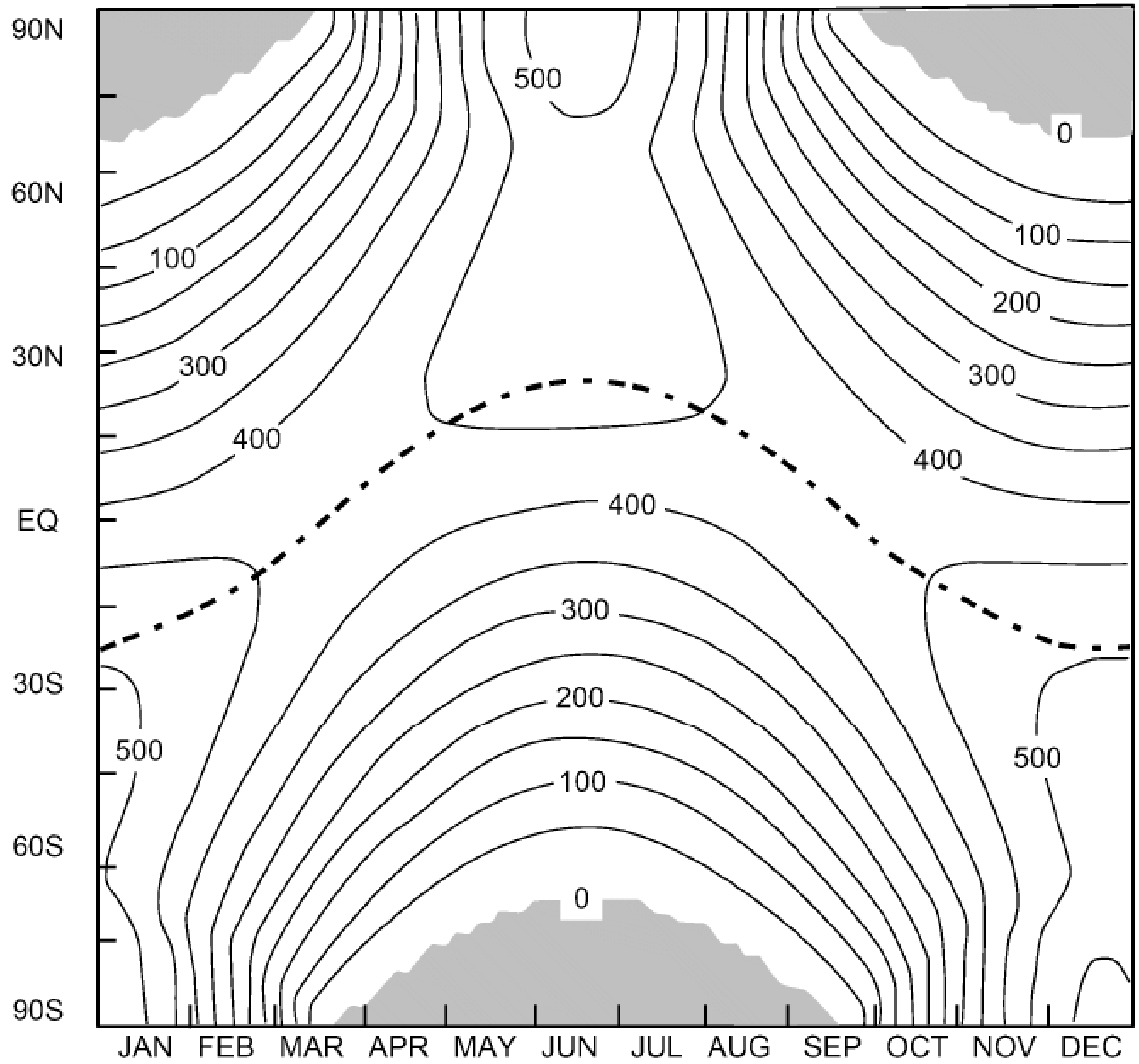
Earth orbit and the seasonal cycle



$$ecc = 0.0167$$
$$\varepsilon_{obl} = 23.5°$$
$$PERH = 102.04°$$

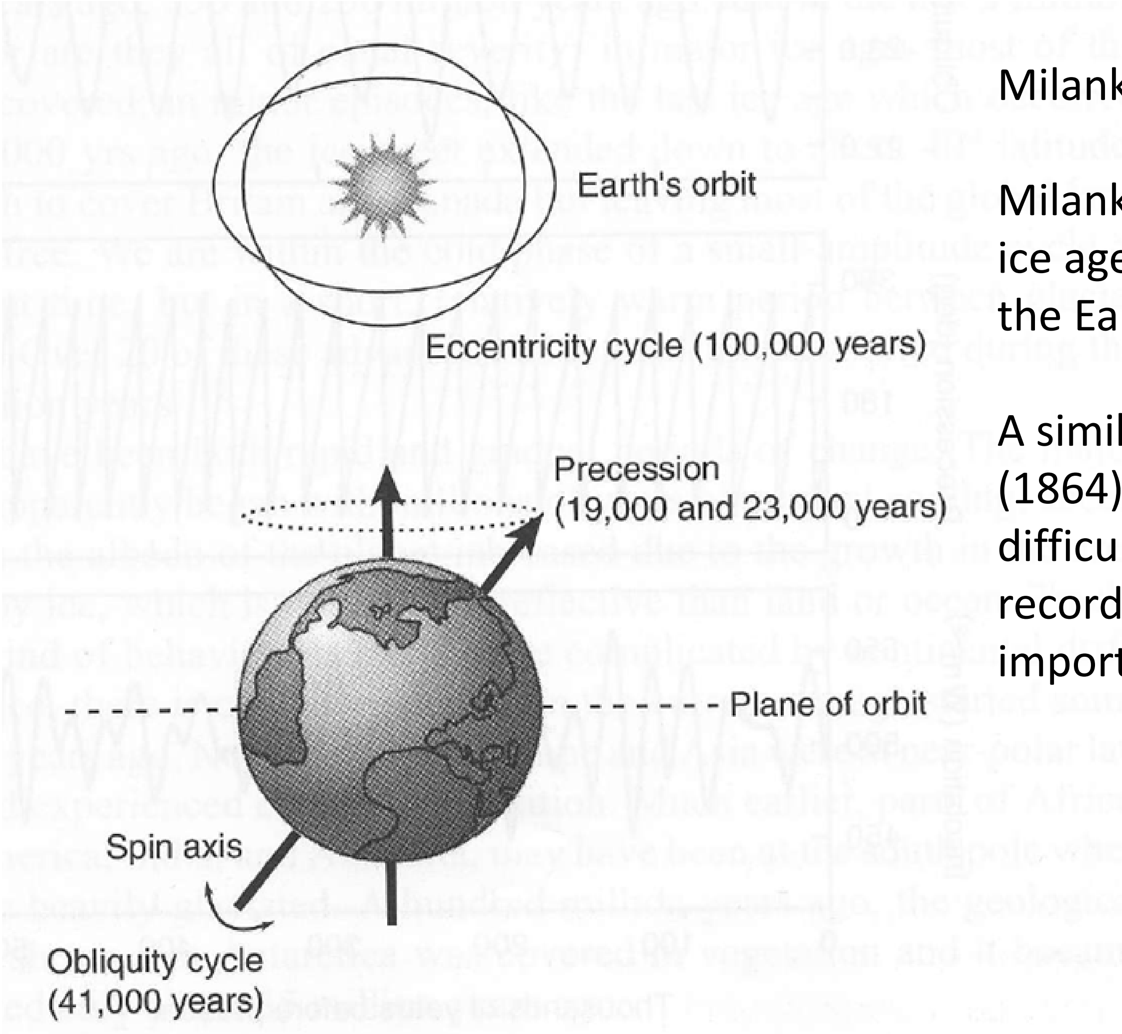


Present day values: eccentricity: 0.0167, obliquity: 23.5°



Mean daily insolation (in W/m^2) on a horizontal surface at the top of the atmosphere as a function of the day and the latitude.

The elements of Earth orbit: Eccentricity, Obliquity and Precession.



Milankovitch theory:

Milankovitch proposed in 1920’es that ice ages on Earth are related to variations in the Earth orbtial elements.

A similar theory was proposed earlier by Croll (1864) but not widely accepted due to difficulties getting accurately dated climate records and determine which cycle is important.

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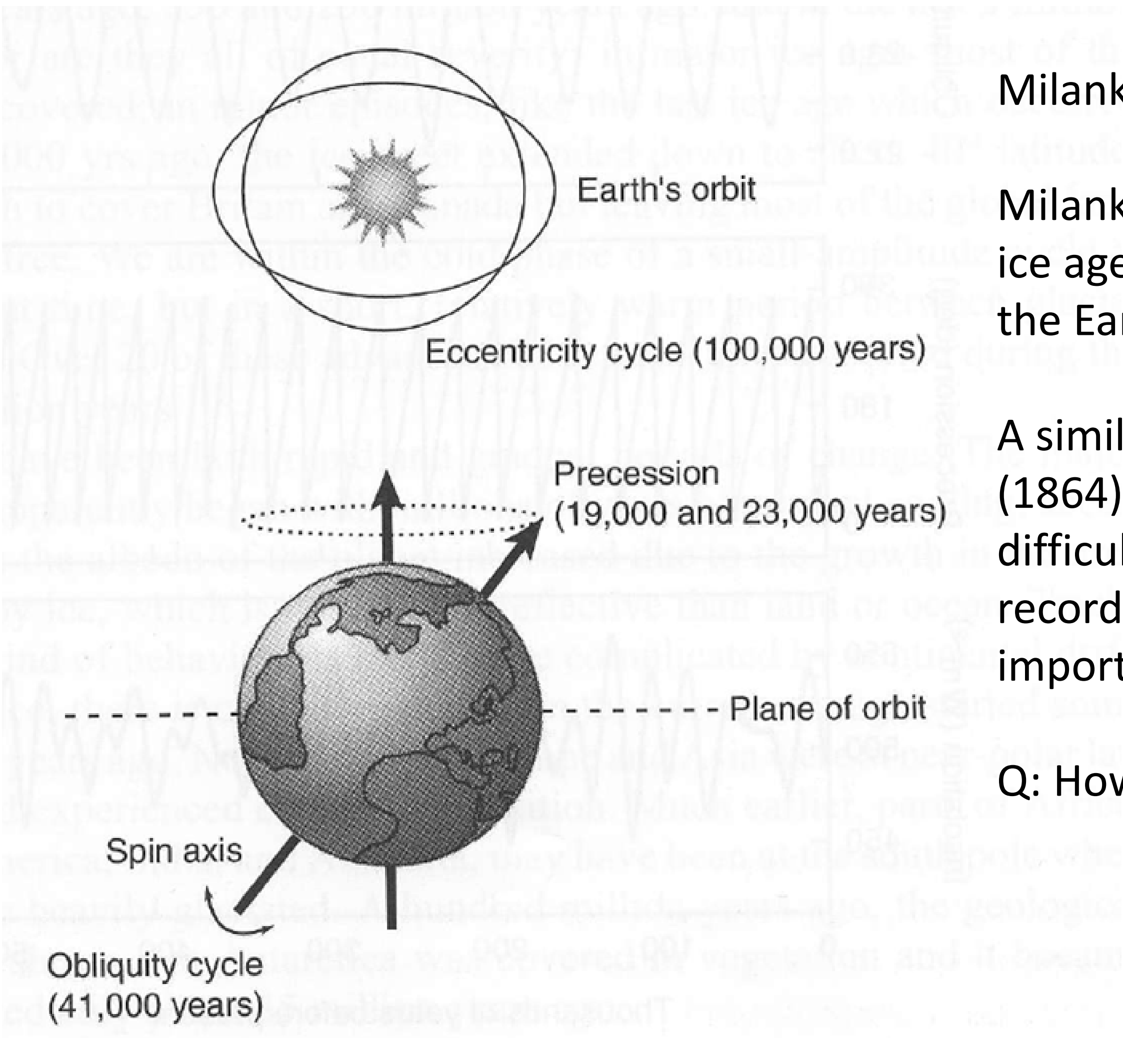

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Q: How can orbital elements control climate?

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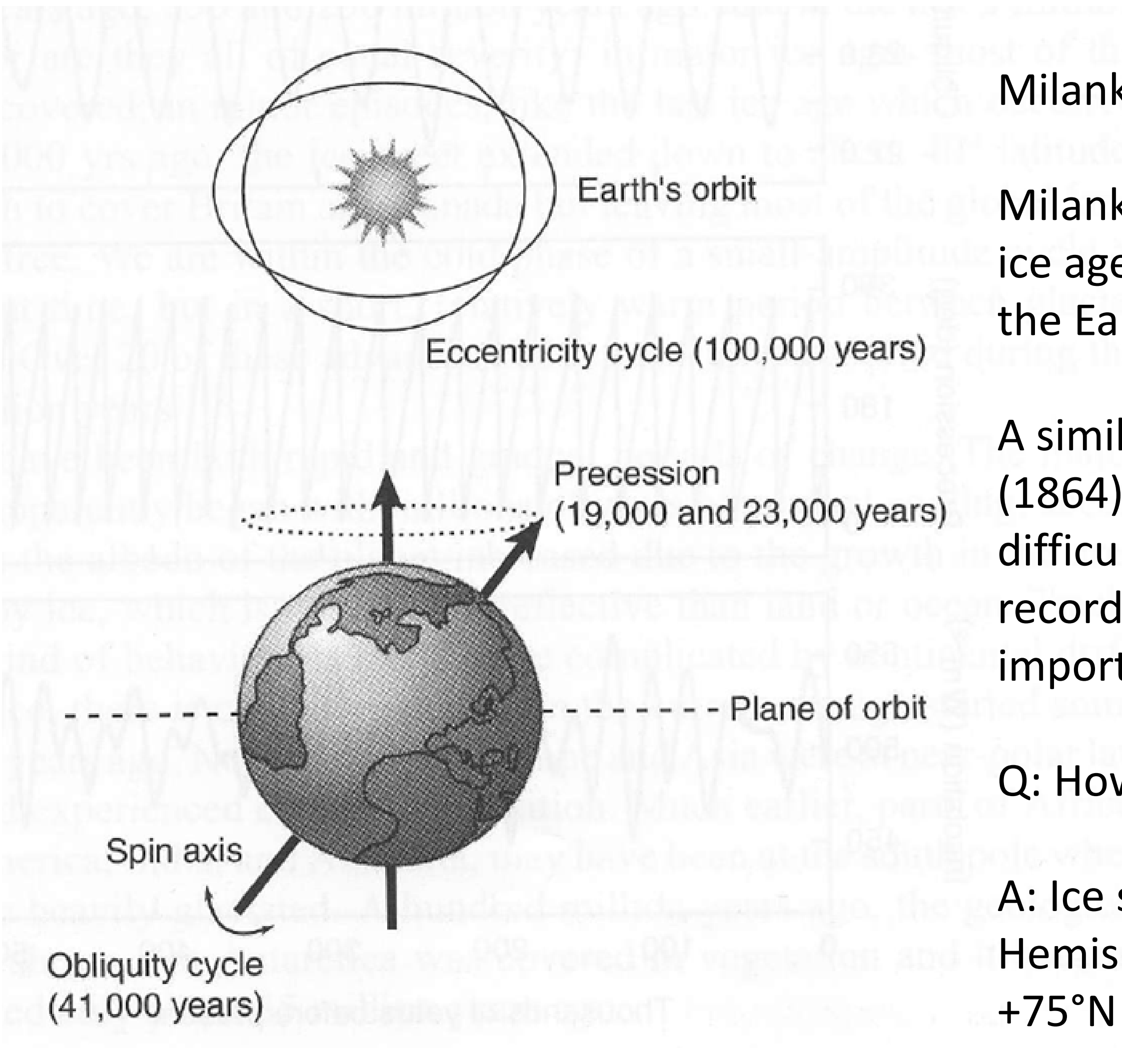

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Q: How can orbital elements control climate?

A: Ice sheets can grow in the Northern Hemisphere.

+75°N – permanent ice

+65°N – ice cover is sensitive to summer melt

+45°N – only ice in winter

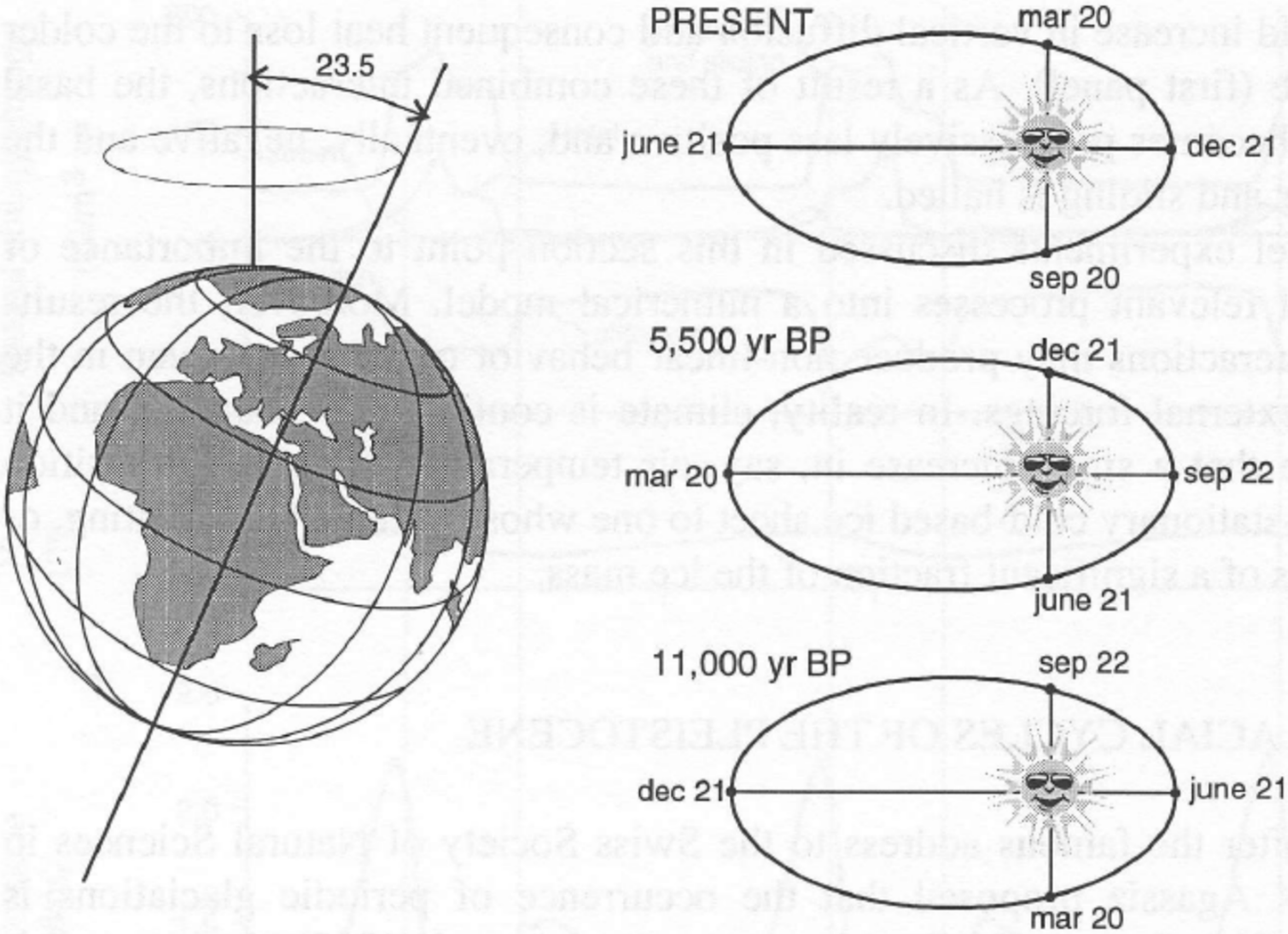
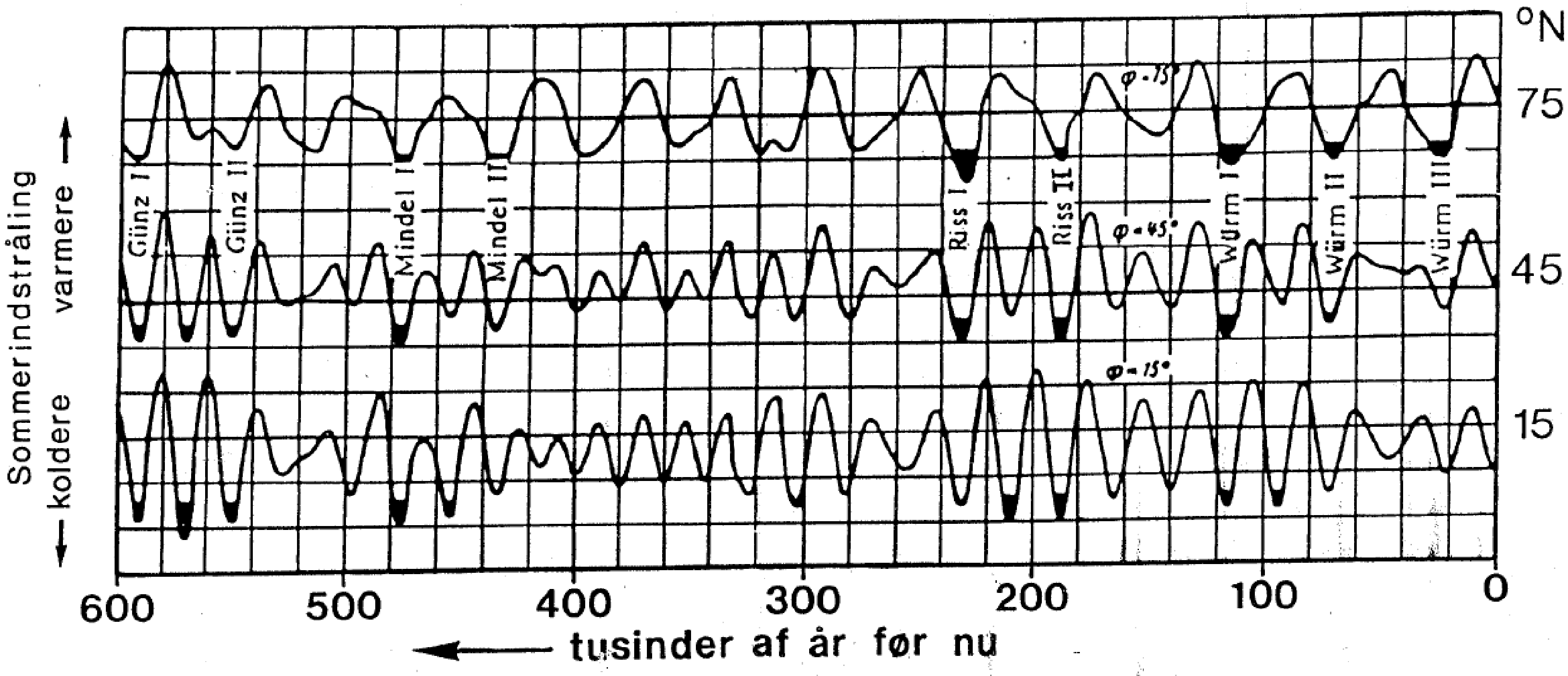


Figure 9.20. Left: precession of the Earth, the rotation axis moves around a circular path with a period of about 23 kyr, while the tilt of the axis varies by about 1.5° on either side of the average angle of 23.5°. Right: precession of the equinox, showing how the seasons travel around the orbit of the Sun with a period of about 22 kyr (after: Imbrie & Imbrie 1979).



MILANKOVITCH 1941

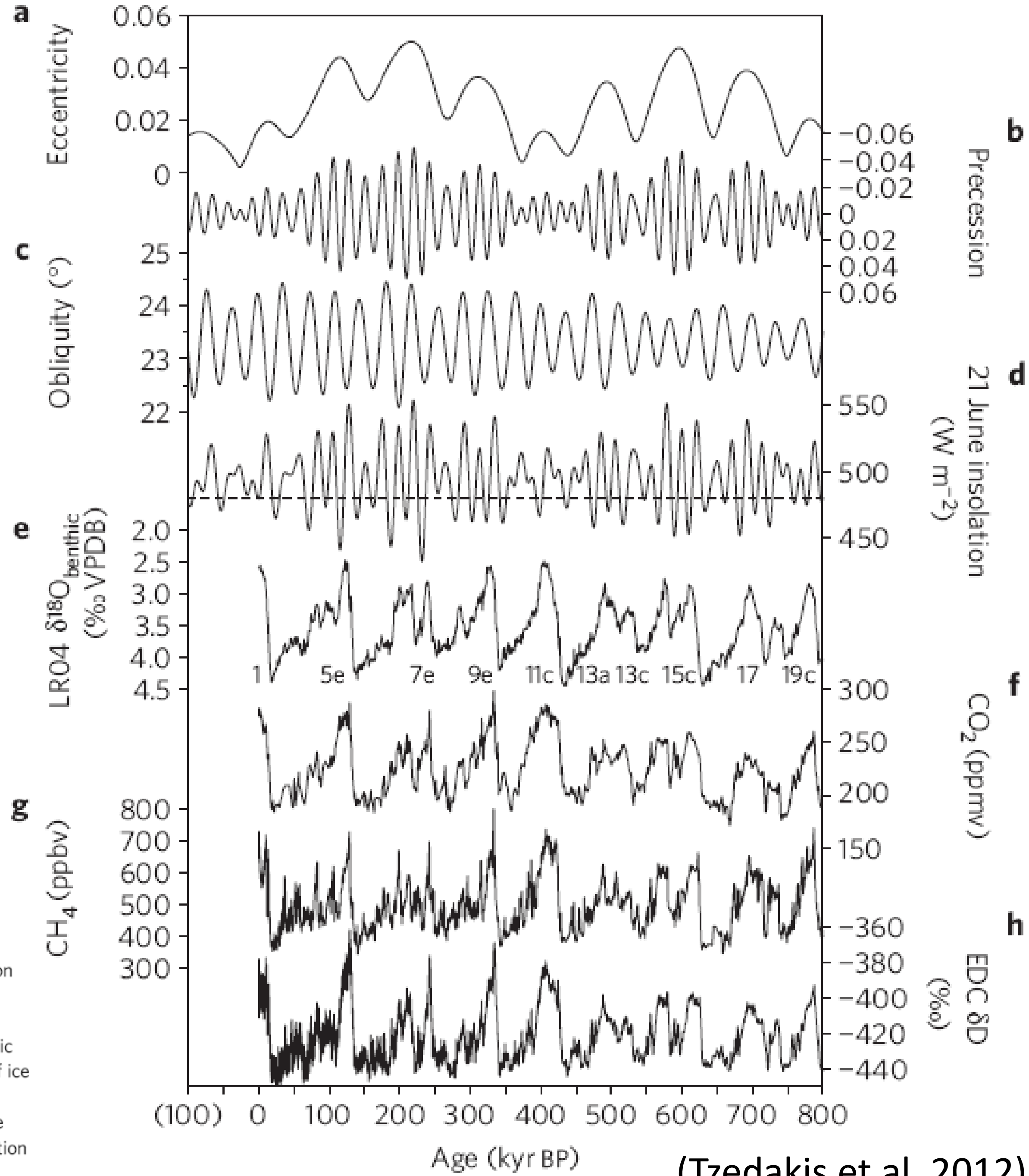
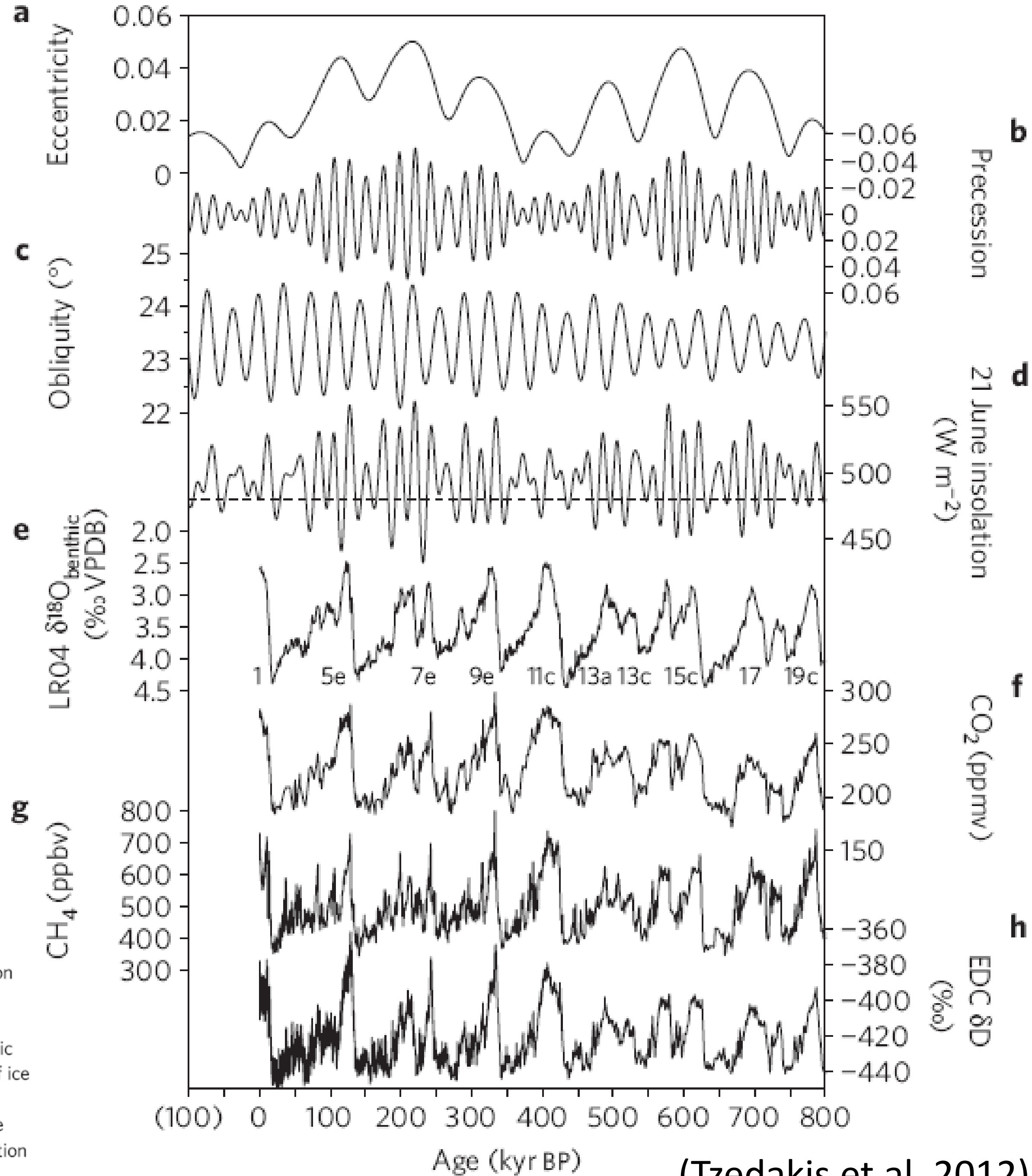


Figure 1 | Astronomical parameters 100 kyr after present—800 kyr BP and palaeoclimatic records 0–800 kyr BP. **a**, Eccentricity[29]; **b**, precession index, plotted on an inverse vertical axis[29]; **c**, obliquity[29]; **d**, 21 June insolation 65° N (ref. 29); **e**, $\delta^{18}O_{benthic}$ record from the LR04 stack[28]; **f**, atmospheric CO_2 concentration in Antarctic ice cores[12]; **g**, atmospheric CH_4 concentration in the Antarctic EDC ice core[13]; **h**, δD composition of ice in the EDC ice core[18]. Marine Isotopic Stages and sub-Stages corresponding to interglacials are indicated. Ages in parentheses denote years after present. The dashed line indicates the current 21 June insolation level at 65° N.

(Tzedakis et al. 2012)

What do we know:

- Ice volume varies on frequencies predicted by orbital forcing
- Ice sheets build up slowly and retreat quickly.
- The ice volume variations show a strong 100 kyr glacial cycle.
- Ice sheets grow in response to insolation and greenhouse gase forcing



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Simple models of the glacial cycles

Modelling the ice sheet evolution:

- Weertman 1976 – tested the impact of insolation variation on ice sheet evolution.
- Oerlemans 1981 – included a delayed bedrock response and found a 100kyr signal.

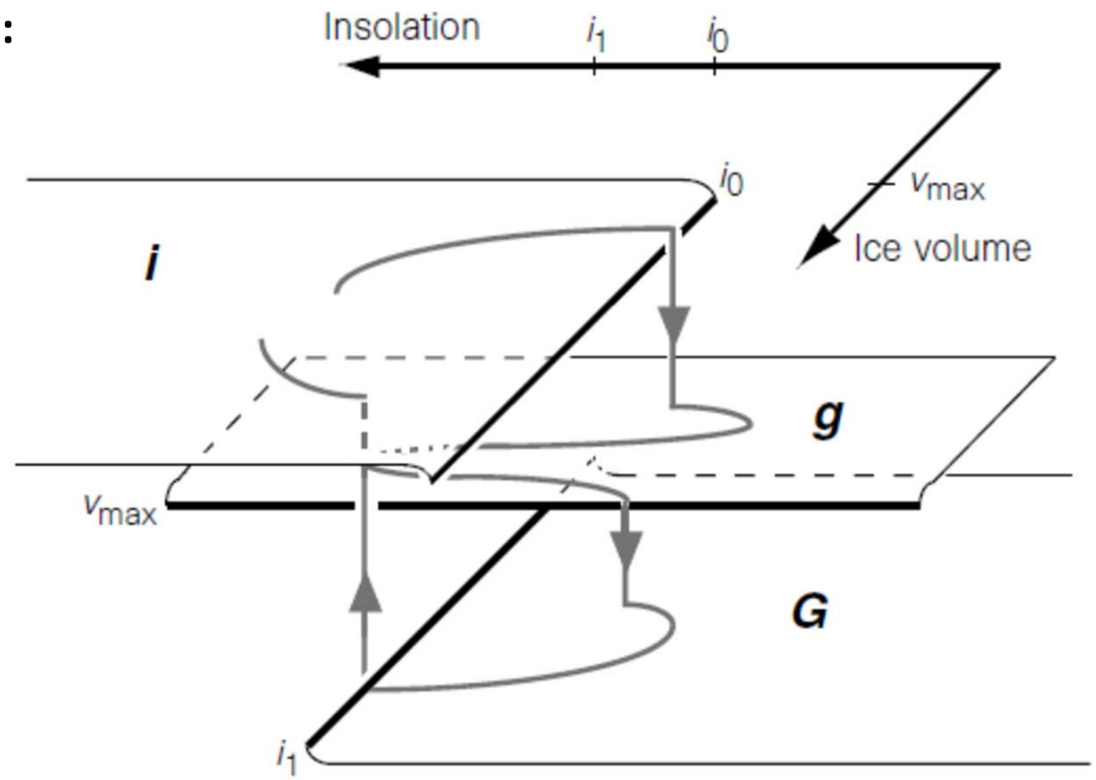
A multiple-state climate model:

- Paillard (1998) – proposed a multiple-state model which shifts between 3 regimes depending on thresholds in ice volume and insolation

Paillard's glacial cycle model

Insolation forcing of glacial cycles:

- Daily insolation at 65°N



3 Regimes:

- i (interglacial)
- g (mild glacial)
- G (full glacial)

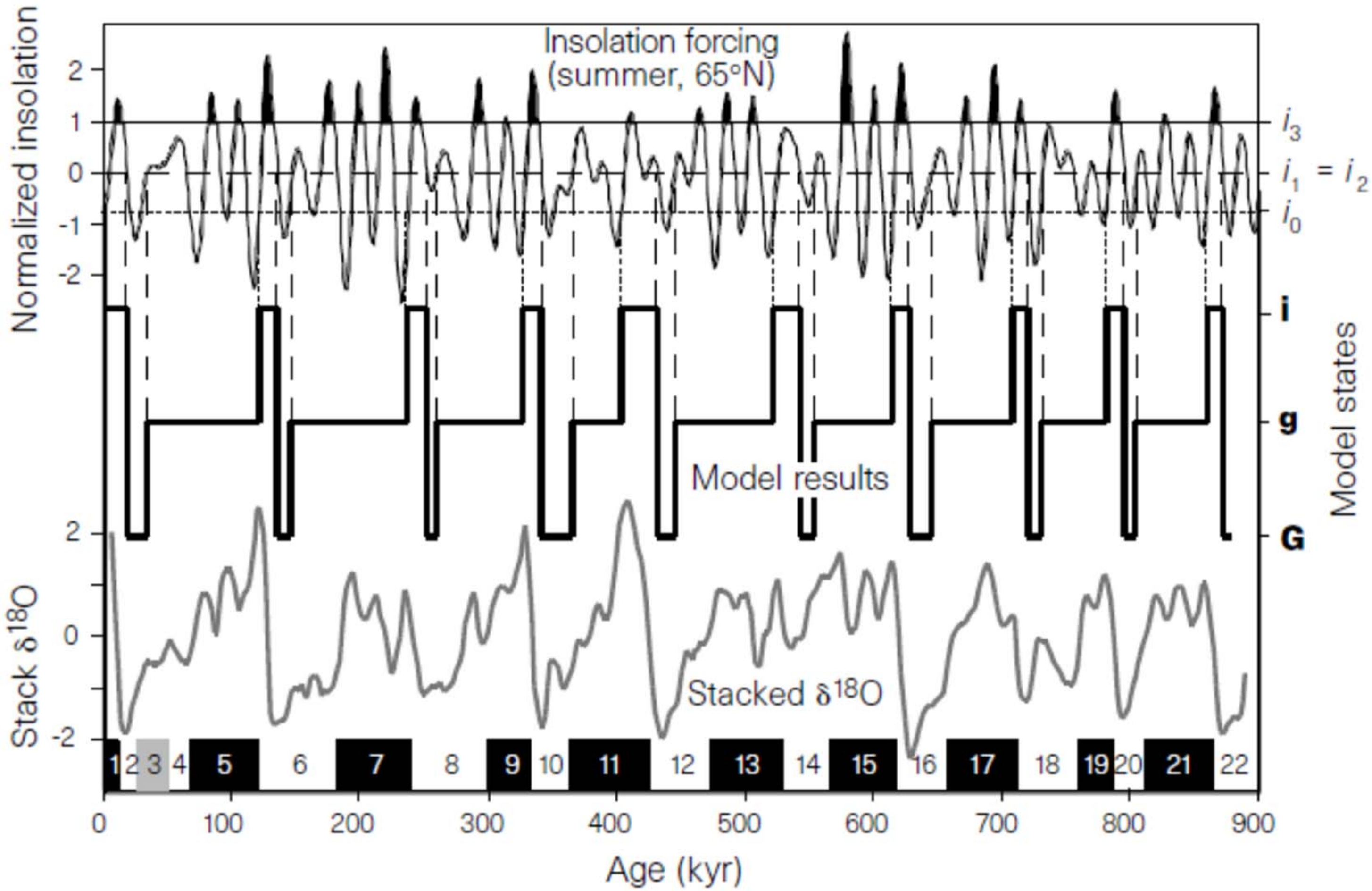
Transitions are one-way:

- i – g: when insolation < i_0
- g – G: ice volume > v_{max}
- G – i: when insolation > i_1

- g – i: impossible, insolation threshold assumed beyond reach
- i – G: Forbidden
- G – g: Forbidden

The ice sheet needs a minimum time t_g to grow and exceed v_{max} while in state g
The g – G transition can only occur if the last insolation maximum was below level i_3 .
The g – G transition can occur at the next insolation decrease after an insolation maximum < i_2

Paillard's glacial cycle model



Threshold values: i_0 = - 0.75, i_1 = i_2 = 0, i_3 = 1.
The minimal duration of the g regime is t_g = 33 kyr.

Support of the Milankovitch theory:

- Ice volume varies at frequencies predicted by orbital forcing.

Unresolved issues:

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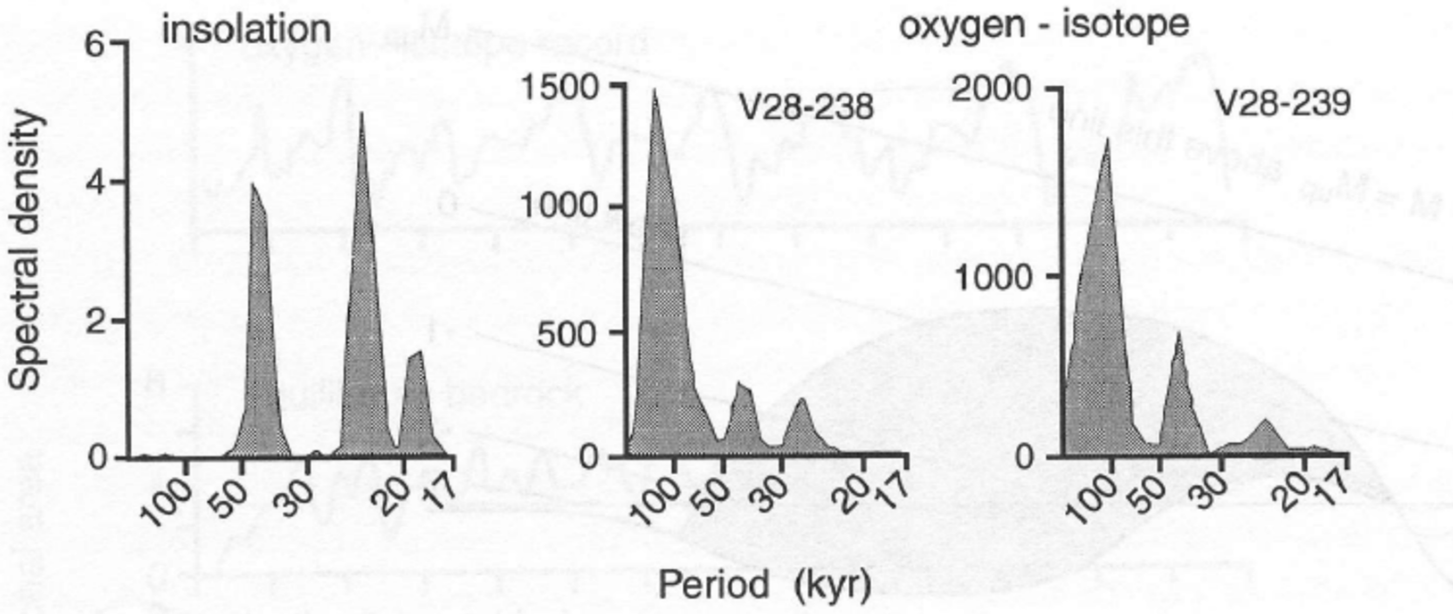
- Why is there no precession cycle in climate records from >1Myr?



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Support of the Milankovitch theory:

- Ice volume varies at frequencies predicted by orbital forcing.

Unresolved issues:

- Why are ice sheets build-up and collapse so different in duration (90kyr vs. 10kyr)
  different patterns of accumulation and ablation?
  Collapse behaviour of a large ice sheet?

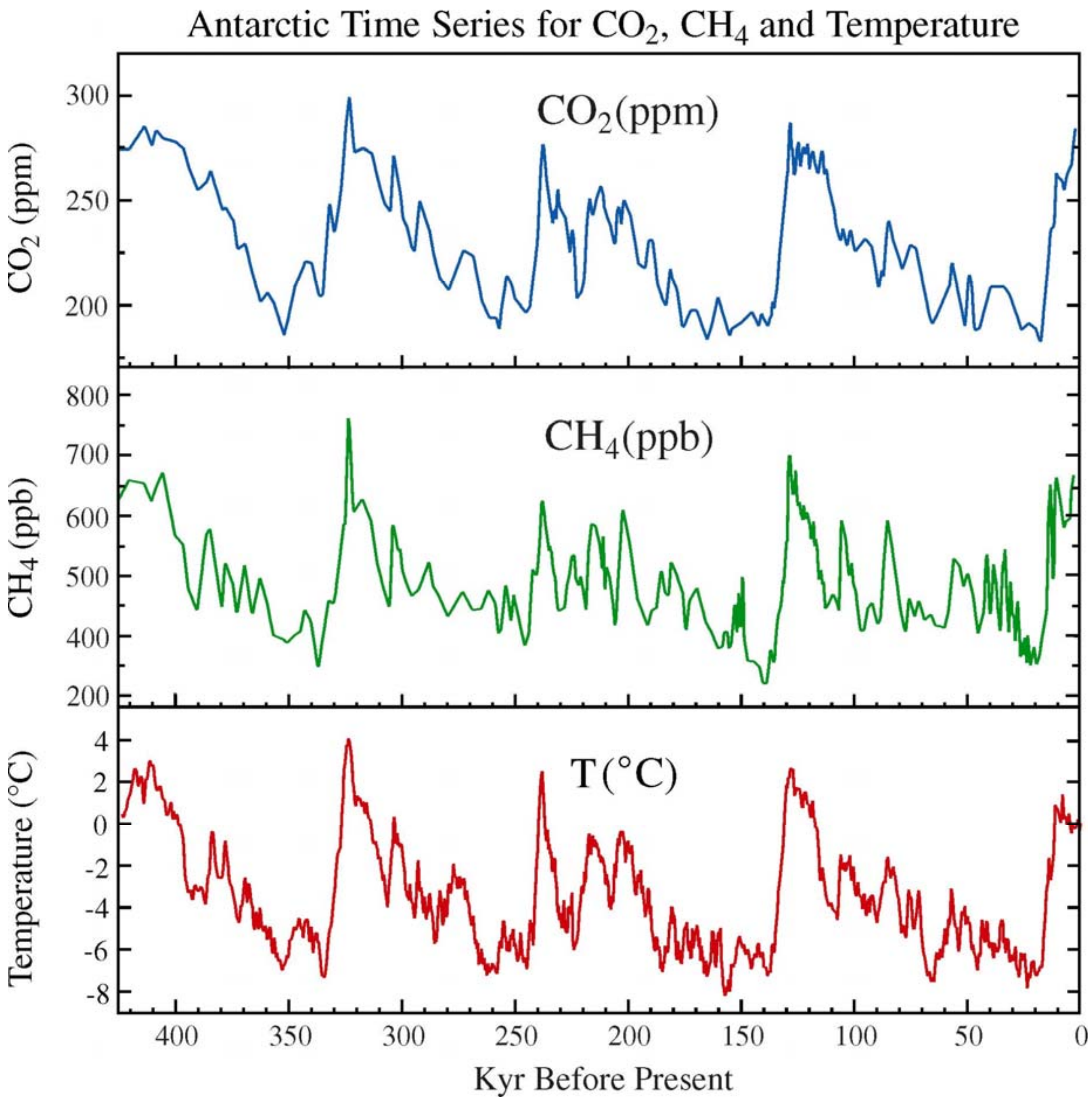
- Why is the 100kyr cycle so strong in climate records?
  feedback with the lithosphere?
  large ice sheets become unstable due to melting at the base?

- Why did the dominant cycle change from 40 kyr to 100kyr?
  Gradual erosion of basal soft sediments allowed the ice sheets to grow larger?
  Gradual cooling allowing the ice sheet to grow larger?

- Why is there no precession cycle in climate records from >1Myr?
  The ice sheets were smaller and did not reach south of 60°N?
  The effect from NH and SH cancel out?

The key to understand these issues is understanding the ice sheet dynamics

Paleo forcings and climate response



CO_2, CH_4 and temperature records from Antarctic ice core data

Source: Vimeux, F., K.M. Cuffey, and Jouzel, J., 2002, "New insights into Southern Hemisphere temperature changes from Vostok ice cores using deuterium excess correction", *Earth and Planetary Science Letters*, **203**, 829-843.

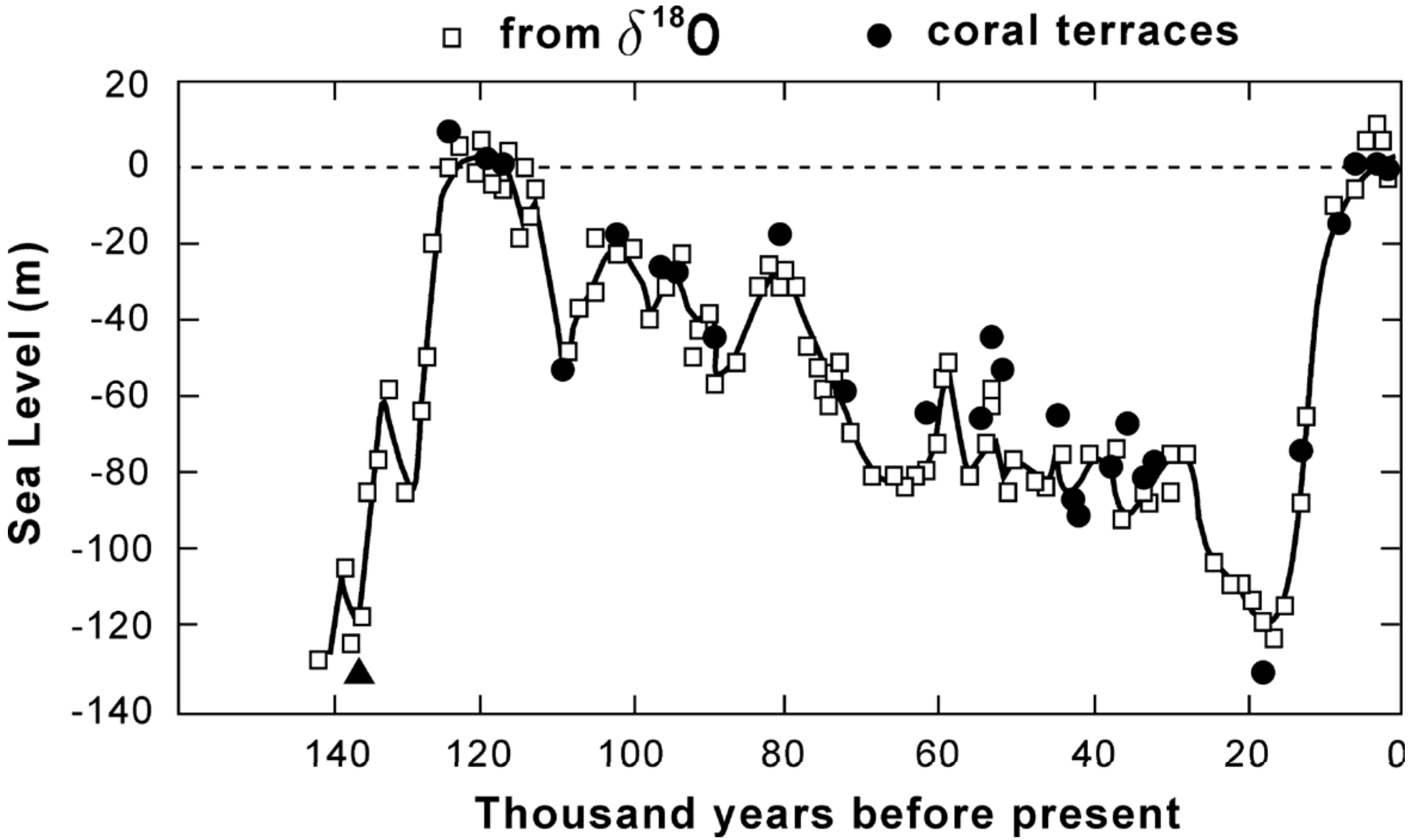
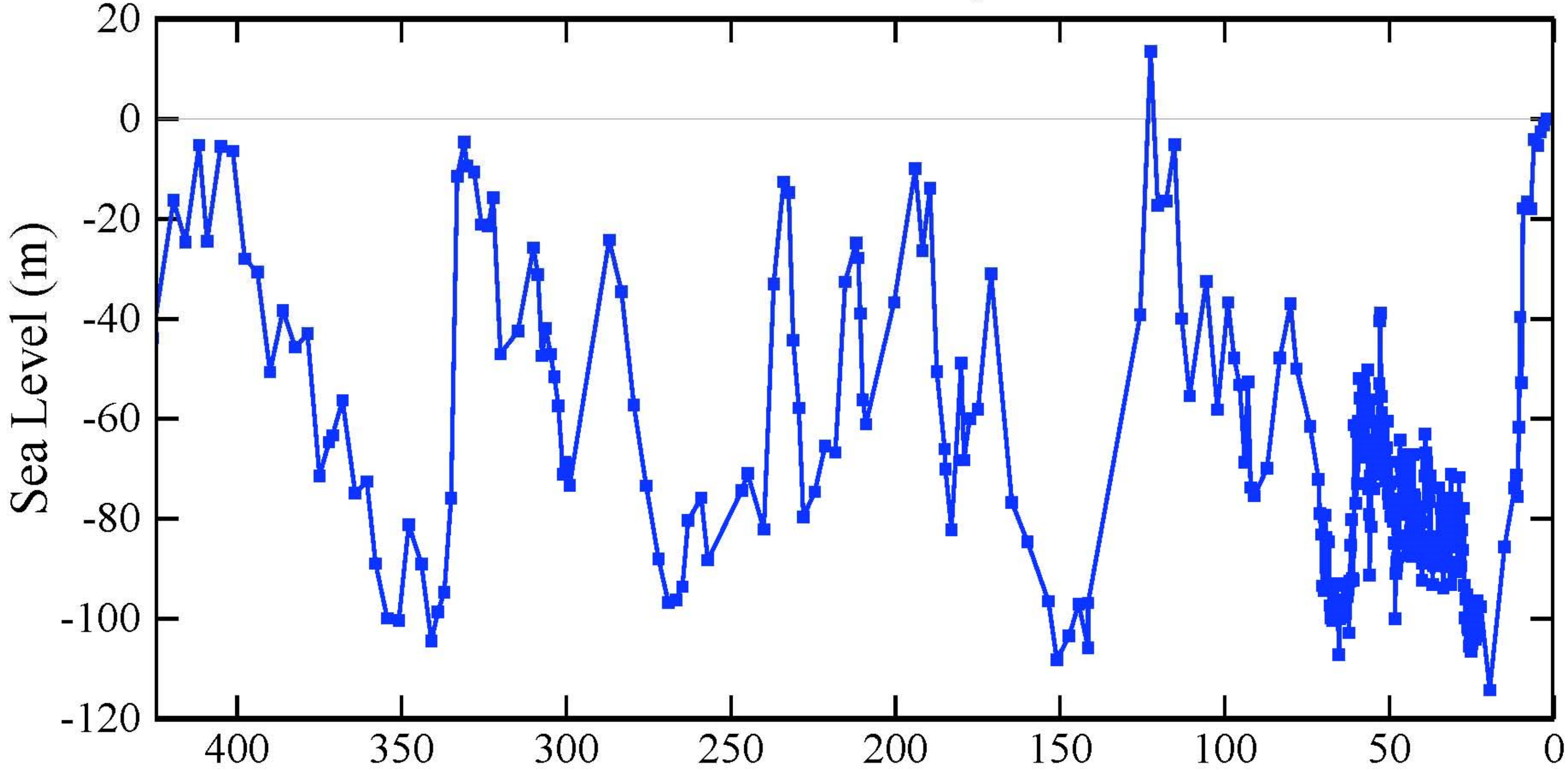


FIGURE 13.4

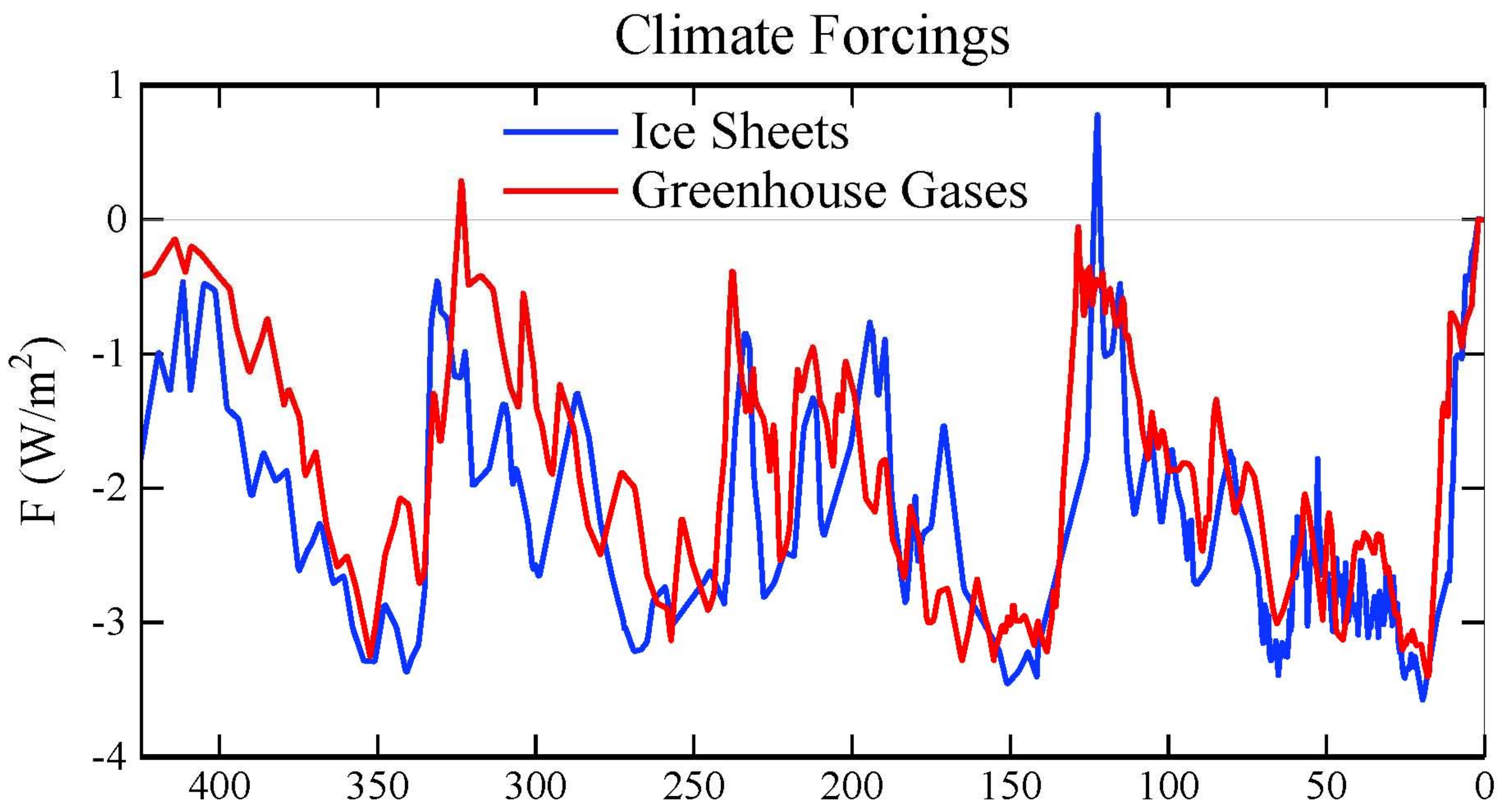
Variation of sea level over the last 140 kyr, estimated from two independent proxies. Adapted from Chappell et al. (1996).

Sea Level from Red Sea Analysis of Siddall et al.



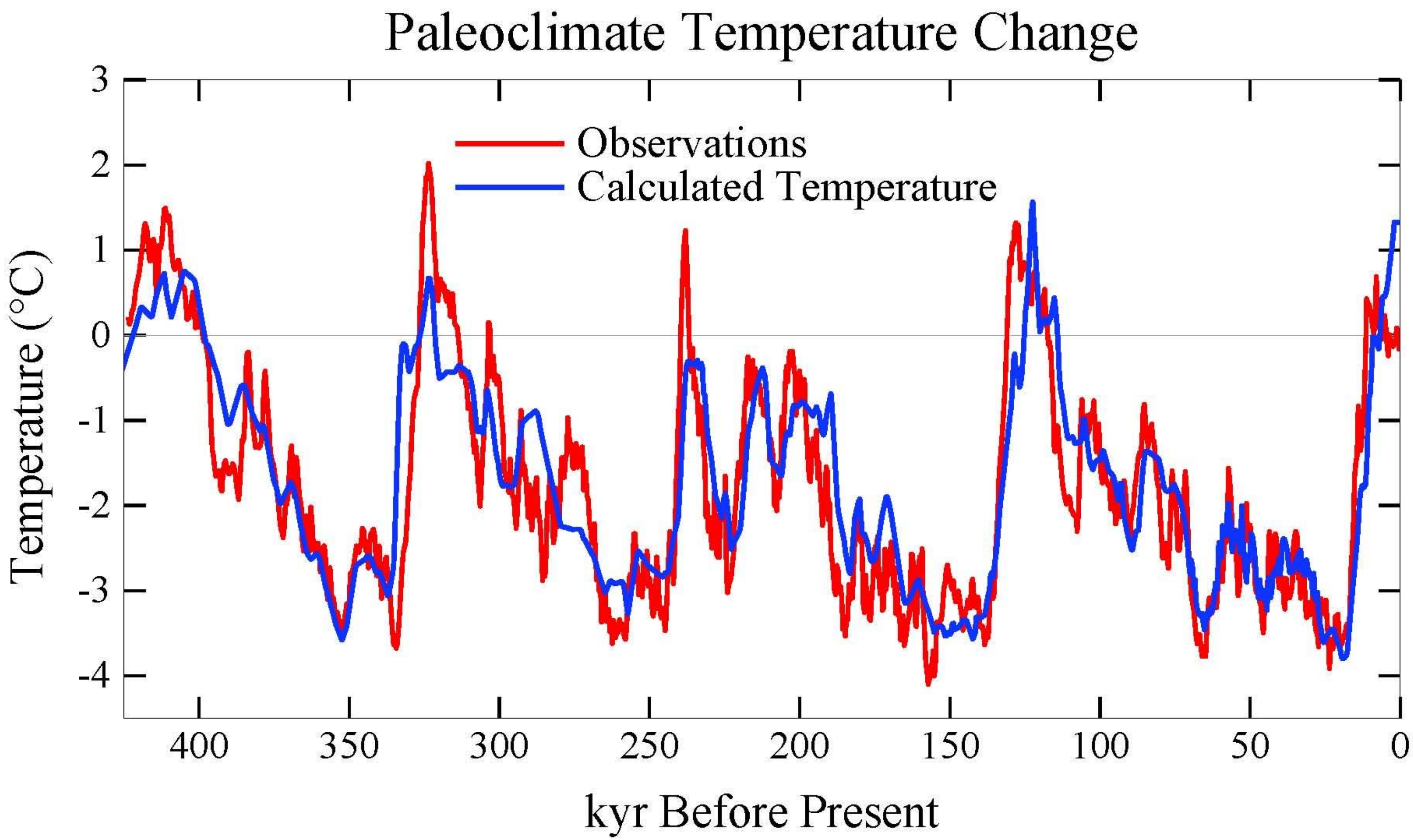
Global sea level extracted, via a hydraulic model, from an oxygen isotope record for the Red Sea over the past 470 kyr (concatenates Siddall's MD921017, Byrd, & Glacial Recovery data sets; AMS radiocarbon dating).

Source: Siddall et al., *Nature*, **423**, 853-858, 2003.



Ice sheet forcing ≅ (sea level)$^{2/3}$

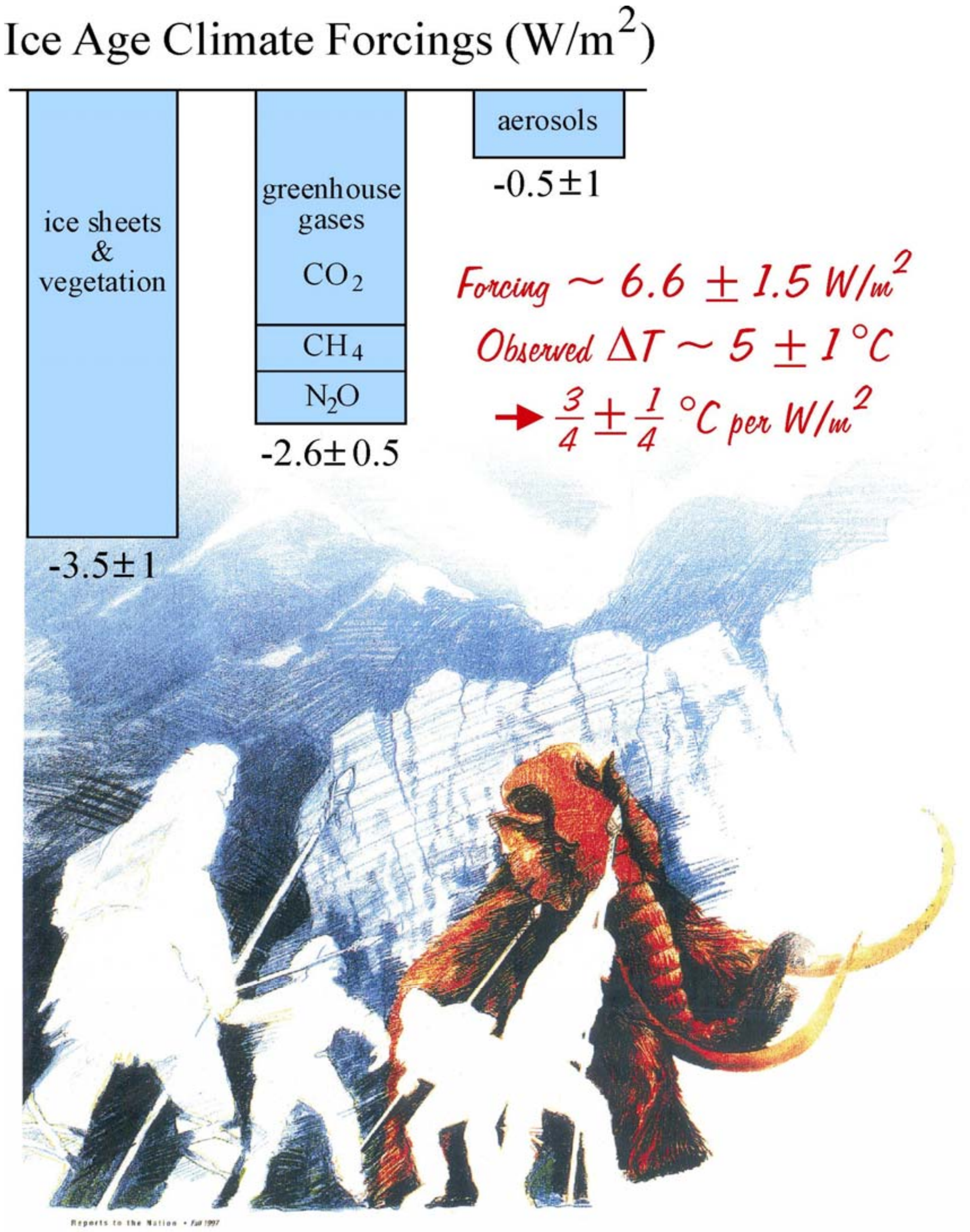
GHGs = CO_2 + CH_4 + N_2O (0.15 forcing of CO_2 + CH_4)



Observations = Vostok ΔT/2.

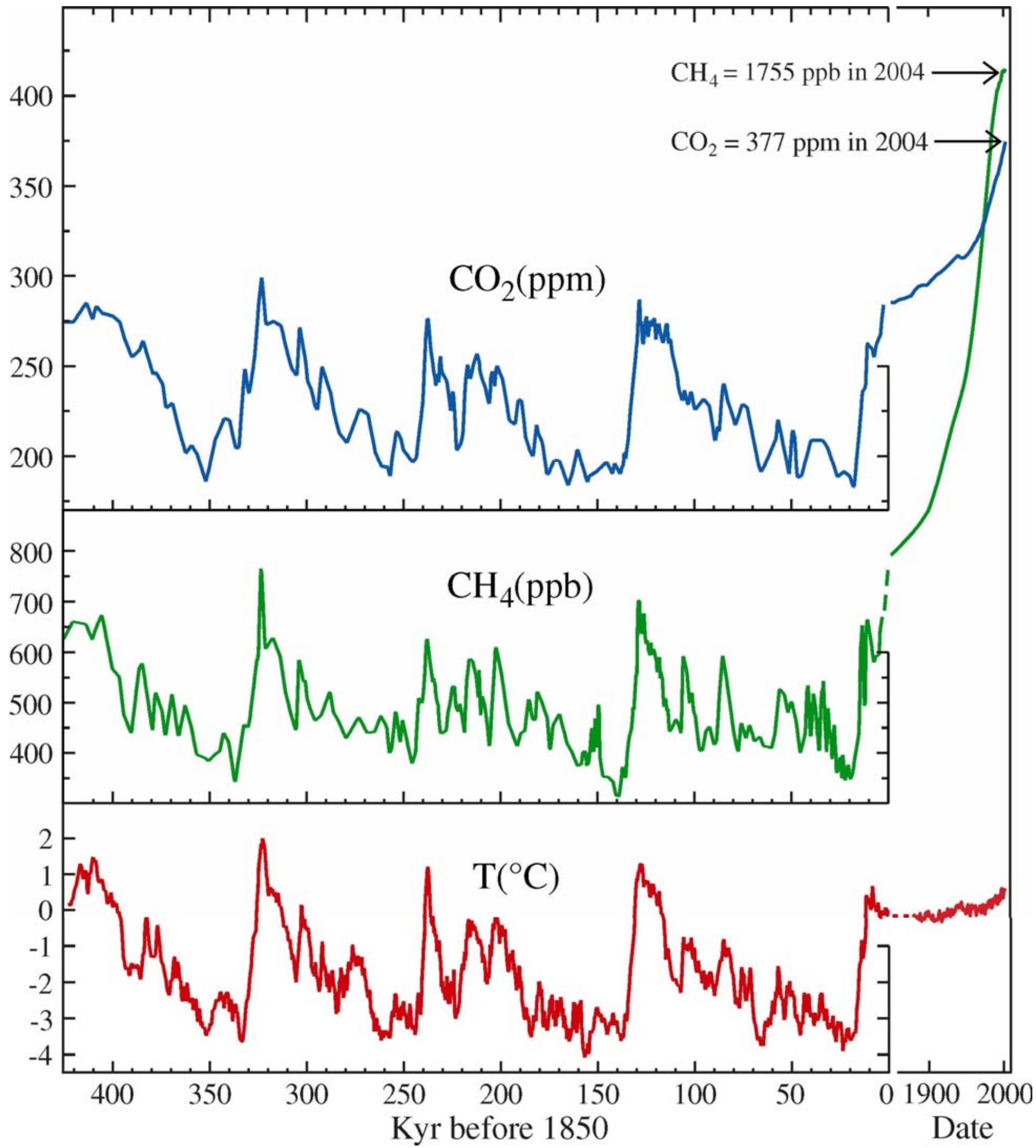
Calculated temperature = Forcing x 0.75°C /W/m^2

Ice Age Forcings
Imply Global Climate
Sensitivity
~ ¾°C per W/m^2.



Source: Hansen et al., *Natl. Geogr. Res. & Explor.,* **9***,* 141, 1993.

CO_2,CH_4 and estimated global temperature (Antarctic ΔT/2 in ice core era) 0 = 1880-1899 mean.



Source: Hansen, *Clim. Change*, **68**, 269, 2005.