Oceans and a changing climate

AOS660

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Orbital cycles / Milankovitch

- Changes in the shape of the Earth's orbit (eccentricity 100Kyr)
- The tilt of the Earth on its axis (obliquity 41Kyr)
- And the season in which the Earth passes closest to the sun (precession of equinox 23 Kyr)

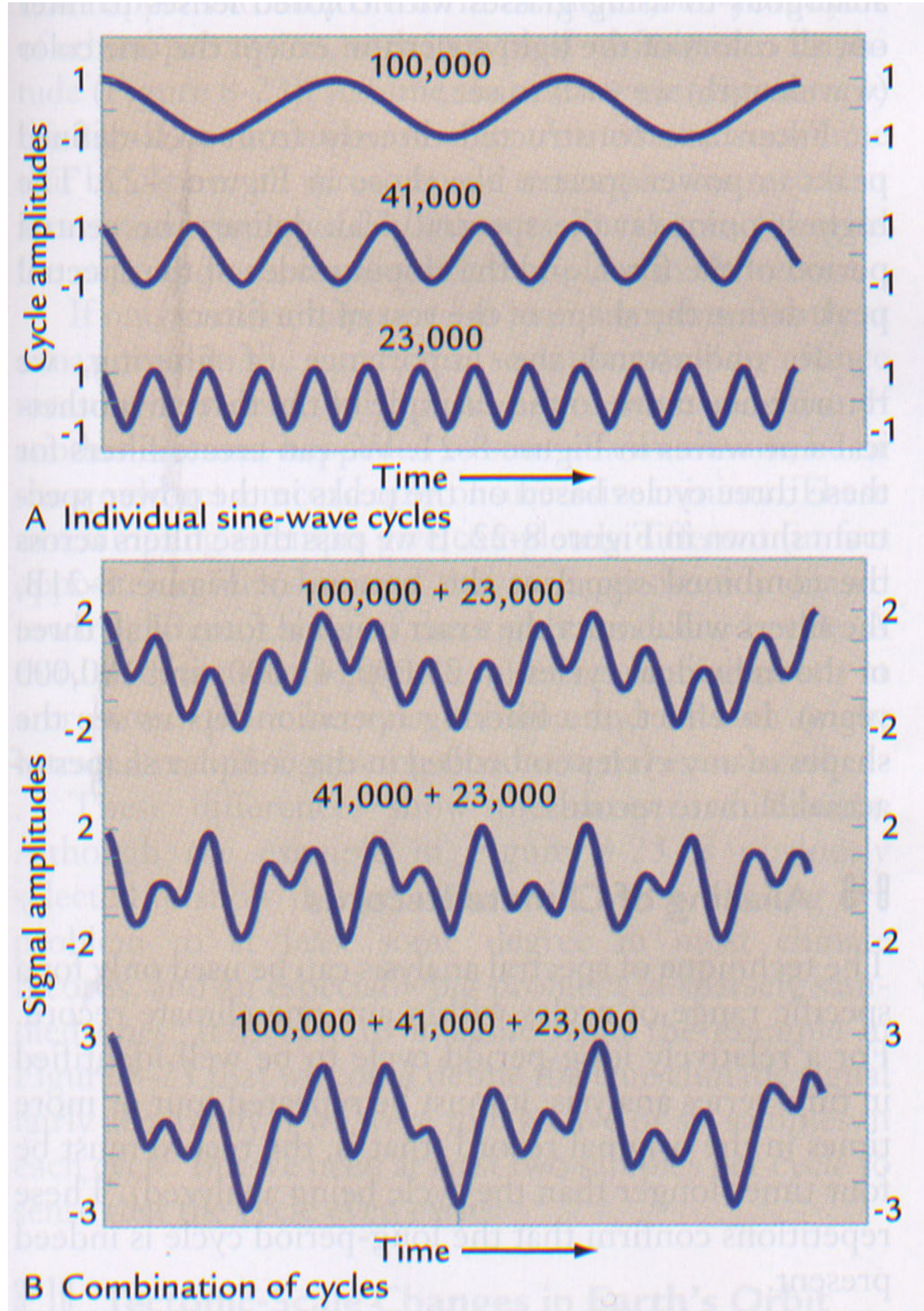
- All modify the amount of radiation received and its seasonal distribution at any point
  - This then modifies glacier growth and decay

Combined Cycles

These are the cycles of variation in seasonal radiation due to orbital motions

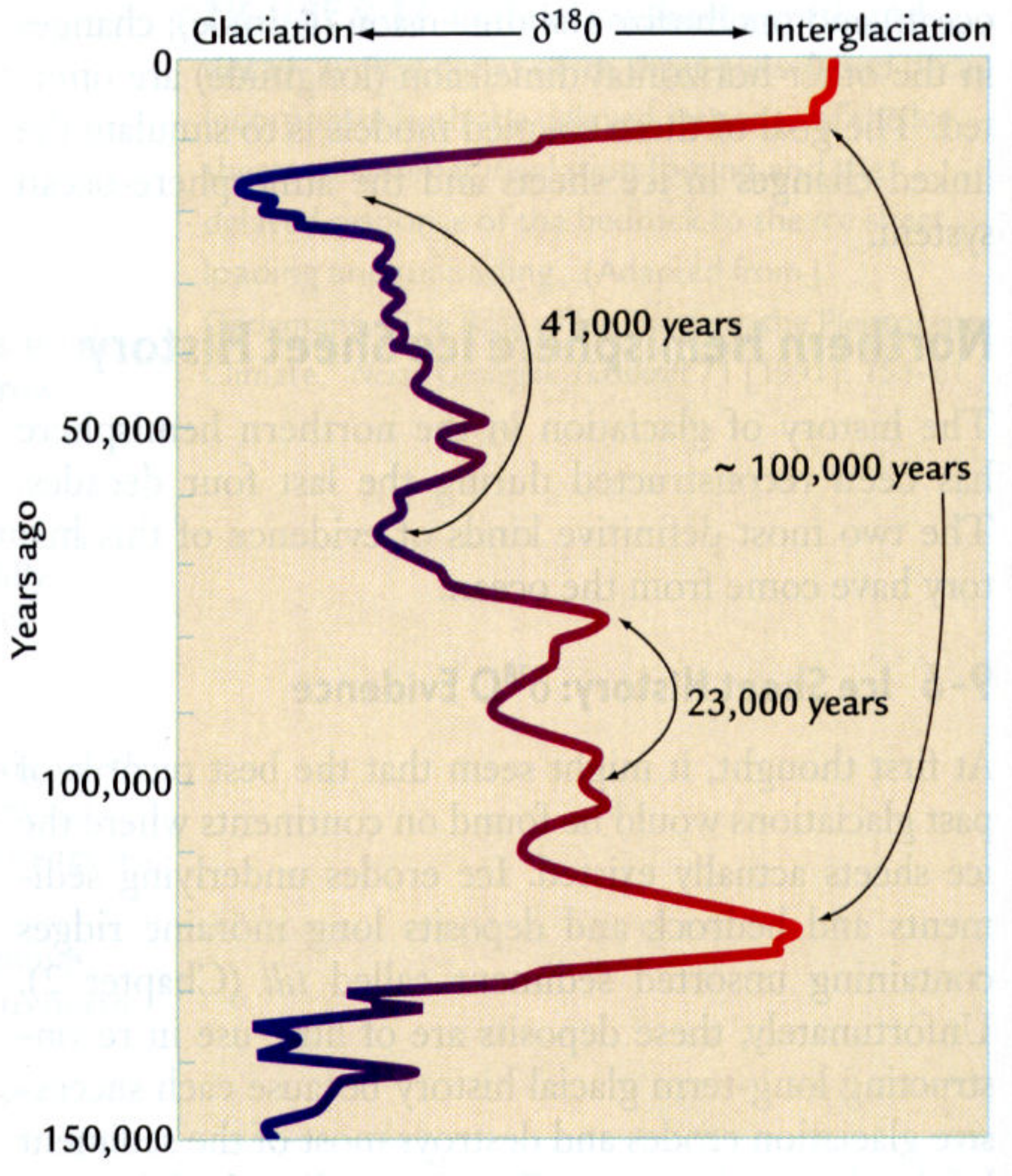
The Earth climate responds to this forcing, both directly (via ice sheets) and indirectly (via feedbacks, such as with greenhouse gases)

We understand orbital forcing well, but many mysteries remain about the climate response

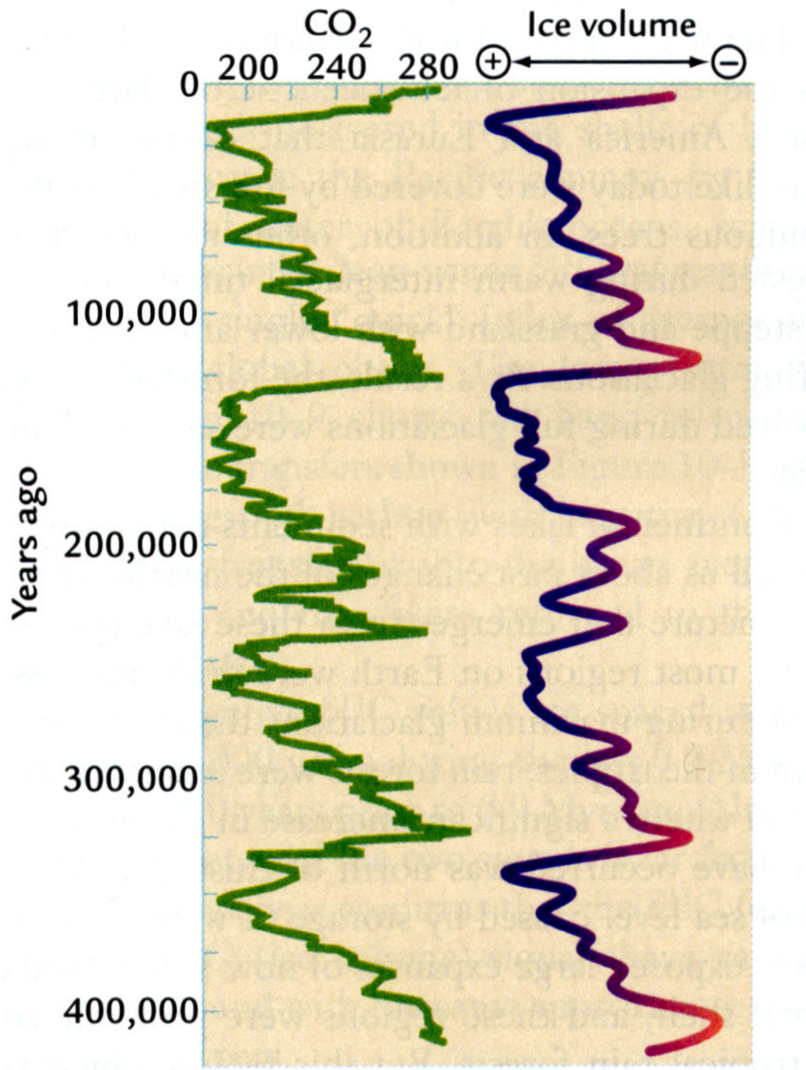


One glacial cycle

Note the slow glaciation and relatively rapid deglaciation



Feedbacks with CO_2, other GHG



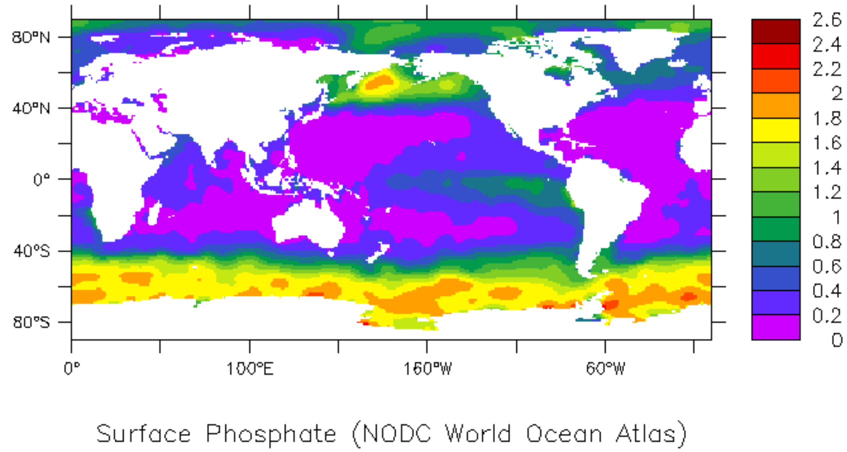
- There's a clear correlation between ice volume and CO_2
- Timing indicates
  - CO_2 leads / forces ice sheets at 23 Kyr
  - CO_2 responds to ice sheets at 41 Kyr
  - Combined response at 100 Kyr of forcing and feedback

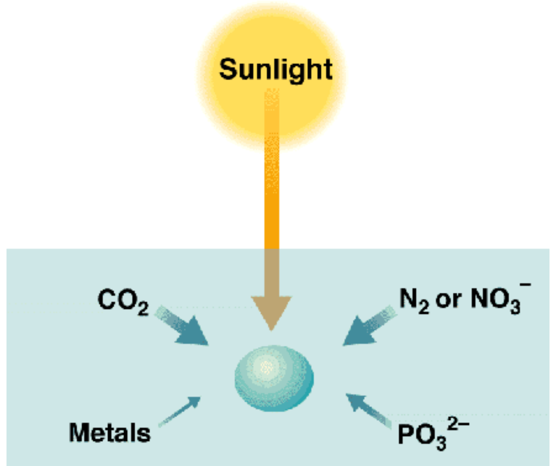
Where does the CO_2 come from?

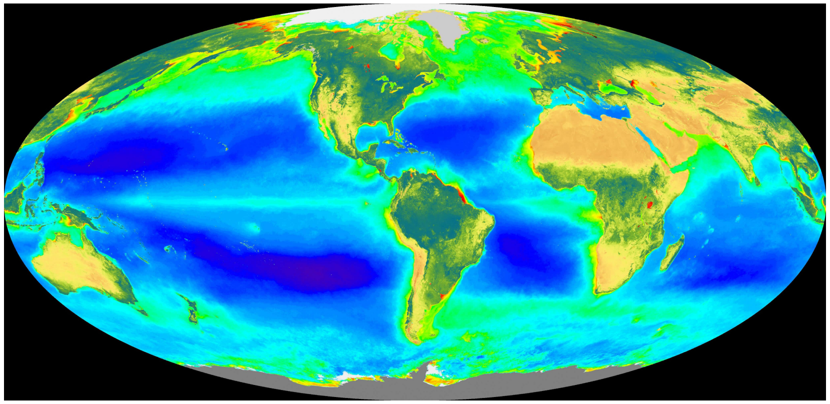
- Land biosphere?
  - No, much land was covered in ice and the rest was more arid. Increases pCO_2 20ppm
- Saltier ocean, due to less volume?
  - Also increases pCO_2 20ppm
- Colder ocean?
  - 2-6 C cooling decreases only 30ppm
- What else could it be?

How can deep ocean feedback with $pCO_2^{atmosphere}$?

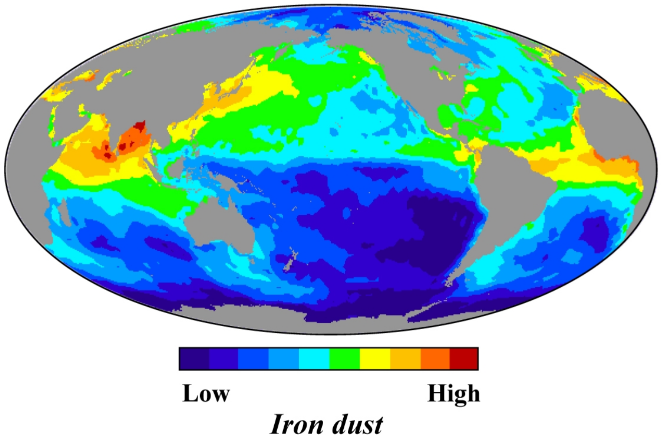
Ocean productivity stimulated in a drier, dustier world?



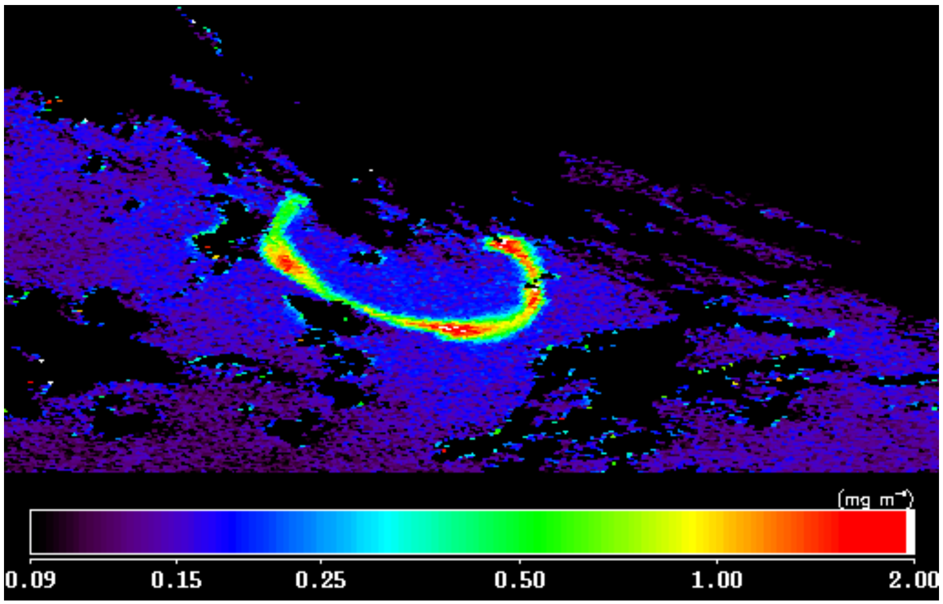




Iron dust in the ocean (NASA)



Direct manipulation, by addition of iron, confirms the hypothesis for productivity



Iron Enrichment Experiment
SoFEX 2002

However, few studies have directly observed an enhancement of atmospheric <u>CO_2 uptake</u>

Perhaps due to the human manipulation being only intermittent, not continuous as the natural would be….

But, observations do not clearly support enhanced productivity in the Southern Ocean during glacial periods…

80-110KyrBP – (0-5KyrBP)

Beginning of glaciation

LGM 18-22Kyr – (80-110KyrBP)

LGM 18-22Kyr – (0-5KyrBP)

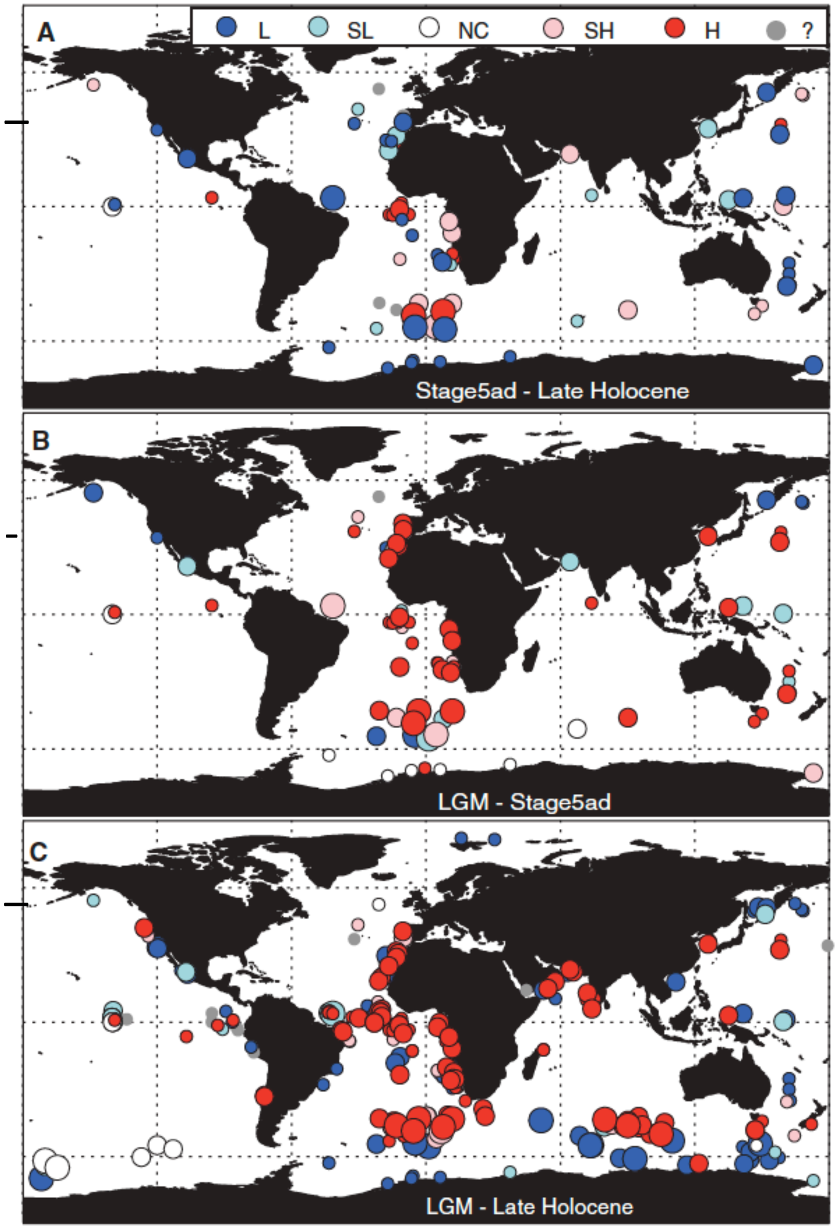


Fig. 2. Relative changes in export production for (A) stage 5a-d (80,000 to 110,000 years ago) minus Late Holocene (0 to 5000 years ago), (B) LGM (18,000 to 22,000 years ago) minus stage 5a-d, and (C) LGM minus Late Holocene. Dark and pale blue circles indicate lower (L) and slightly lower (SL) export production, respectively; dark and pale red circles indicate higher (H) and slightly higher (SH) export, respectively. White circles indicate no change (NC) between the two time periods. Gray circles represent sites where there is no unambiguous consensus between the different types of data. The size of the circle indicates the level of confidence (with small circles indicating low and large circles high confidence) in the assessment of the change in export production (15).

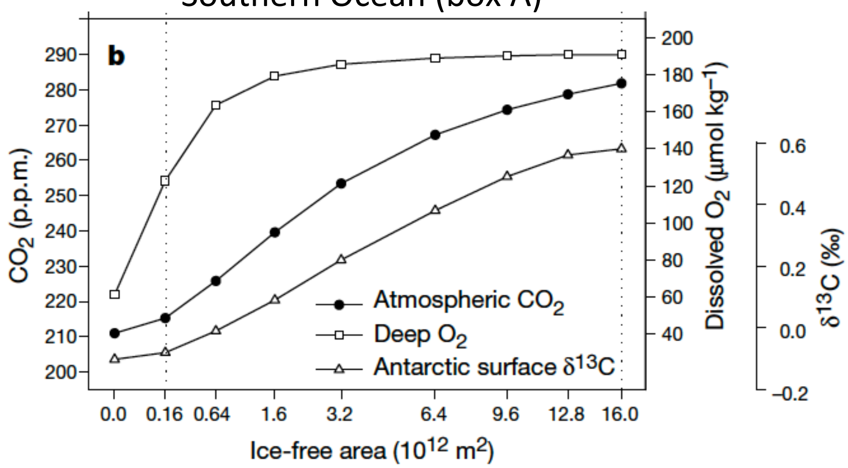
Red = higher productivity

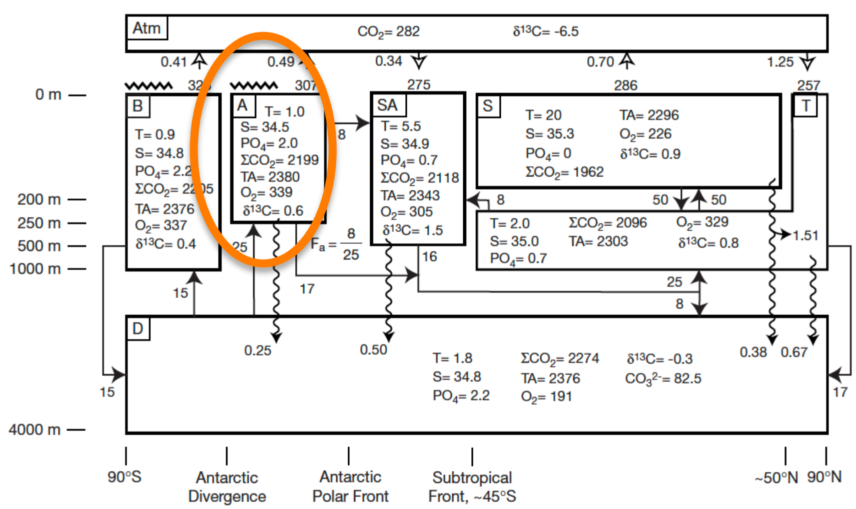
Blue = lower productivity

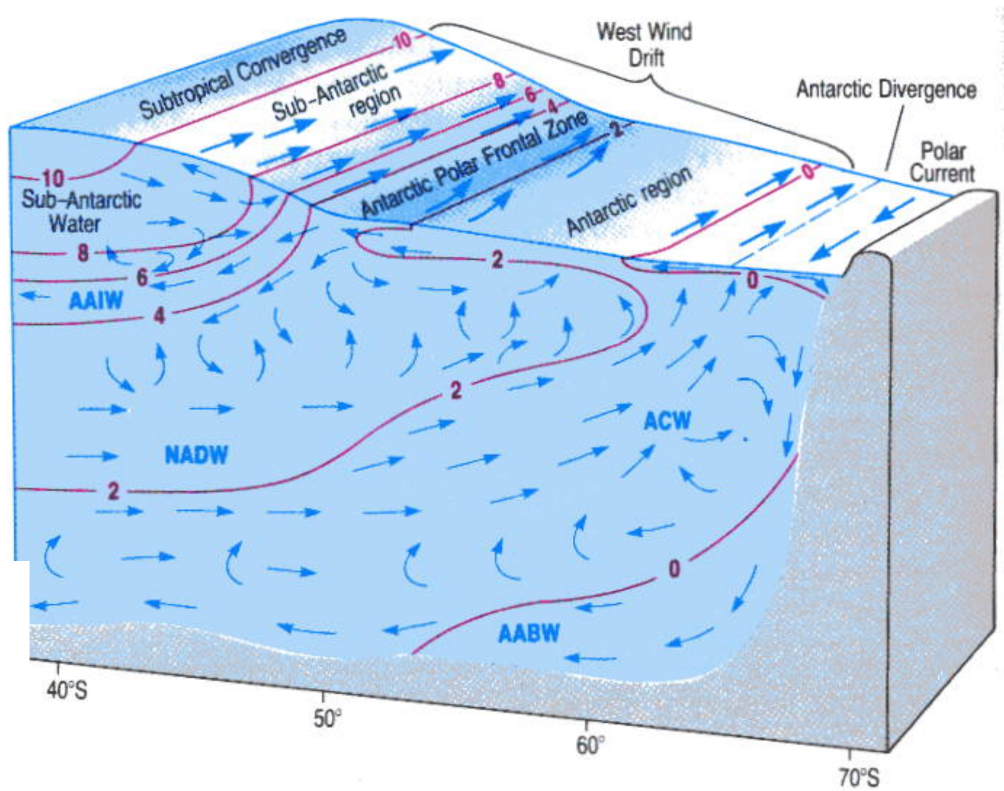
Kohfeld et al. 2005

Did more sea ice limit ventilation of “old carbon” to the surface in the Southern Ocean?

Ice Free Area in non-coastal Southern Ocean (box A)



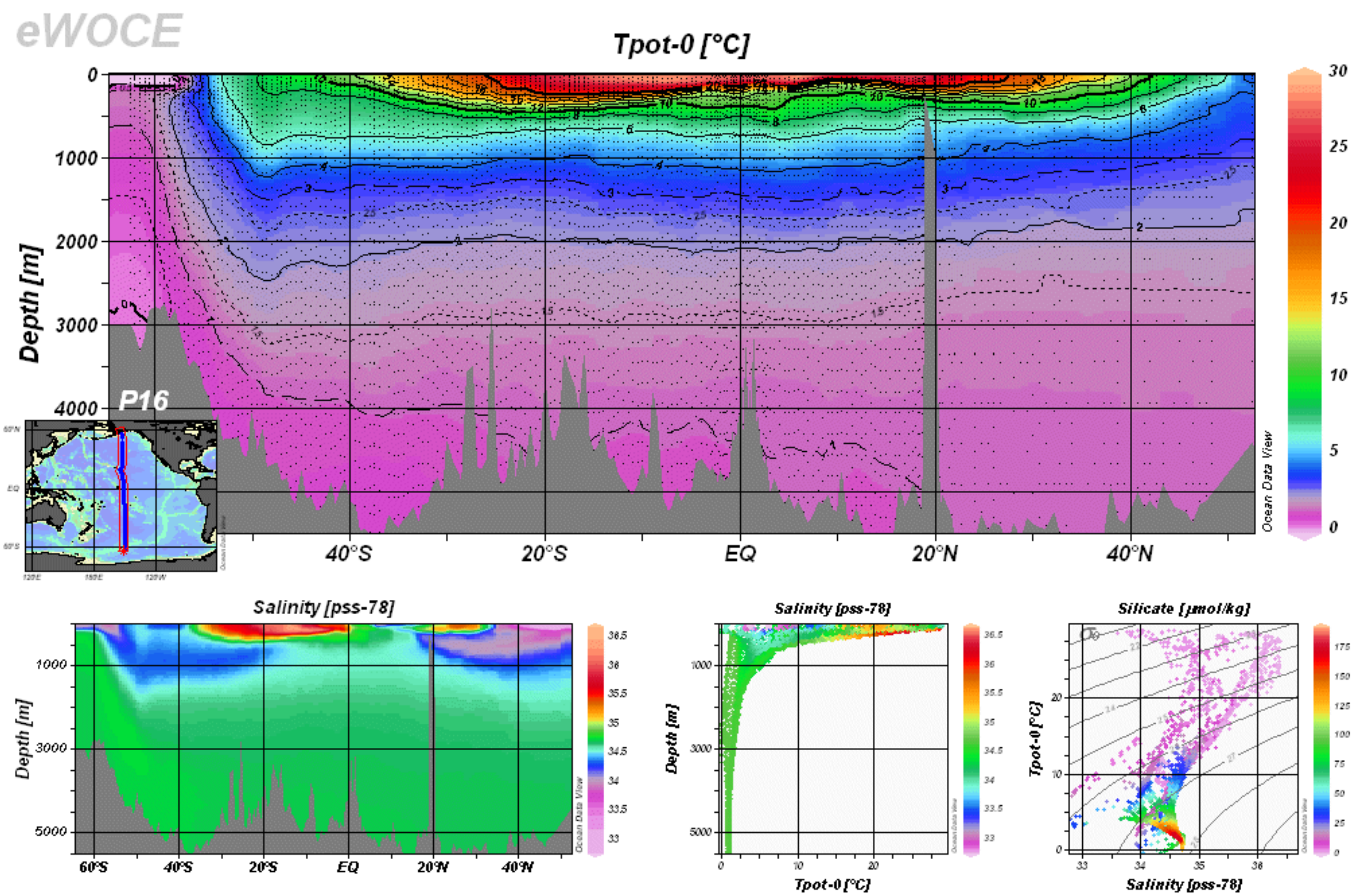




Stephens and Keeling, 2000

Perhaps, MOC was slower when there was more Antarctic Bottom Water and so mixing on the MidAtlantic Ridge was less effective at driving the overturning? … This would let the ocean store more CO_2 at depth…

(Watson and Garabato 2006; Adkins et al. 2002; Sigman et al. 2010)



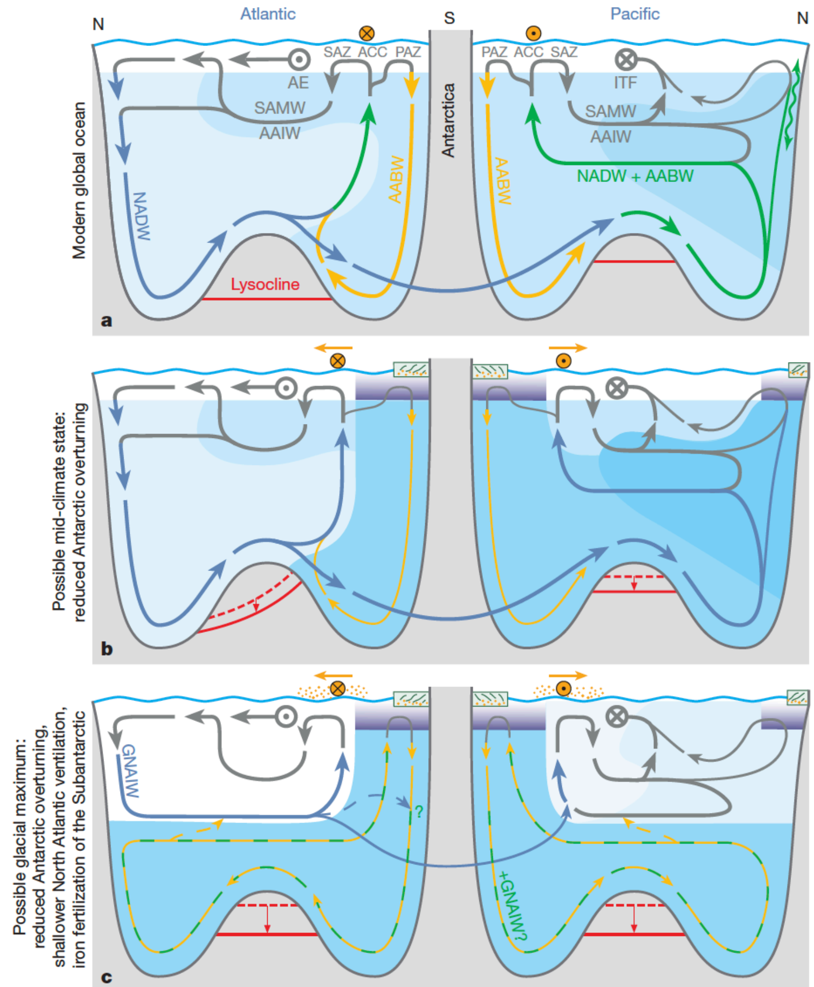


Figure 3 | Summary cartoon of the global ocean today and in two possible ice-age states. a, The global ocean today; **c**, a possible glacial maximum; **b**, a hypothetical intermediate climate state. NADW, North Atlantic Deep Water; GNAIW, Glacial North Atlantic Intermediate Water; AABW, Antarctic Bottom Water (simplistically taken here to represent all Antarctic-formed deep water[27]); AAIW, Antarctic Intermediate Water; SAMW, Subantarctic Mode Water; ITF, Indonesian Through-Flow; AE, Agulhas Eddies (ITF and AE return surface water from the Pacific to the Atlantic, with circled points showing transport out of the page and crosses showing transport into the page); SAZ, Subantarctic Zone; ACC, Antarctic Circumpolar Current; PAZ, Polar Antarctic Zone. Line colours of interior flows indicate their ventilation source region: blue, NADW or GNAIW; yellow, AABW; green, mixed NADW and AABW. Line thickness changes among panels denote changes in flow rate. The steady-state lysocline depth is indicated as a solid red line, with the dashed red line indicating a transient shoaling going into that stage, causing a transient decrease in seafloor $CaCO_3$ burial that increases ocean alkalinity. Deeper blue shading in the interior indicates a higher concentration of regenerated nutrient and thus regenerated (that is, excess) CO_2. In **b** and **c**, PAZ ventilation of the deep ocean is decreased relative to **a** (see the much thinner yellow flow lines in **b** and **c**). This may be the result of an equatorward shift in the westerly winds (orange symbols above the sea surface) that reduces northward transport of surface waters (slight thinning of this and downstream flow lines) and thus allows the freshwater cap in the PAZ to strengthen (purple shading in the Antarctic and also the North Pacific); in the text, other possible mechanisms for reduced PAZ overturning are also considered. Increased sea ice in the glacial Antarctic may have reduced CO_2 evasion during the winter and/or encouraged algal nutrient consumption in the summer by shoaling the mixed layer and releasing a winter's worth of aeolian iron deposition. In **c**, the ice-age dust increase (orange stipples) enhances nutrient extraction in the Southern Ocean surface, especially in the SAZ; the dust increase is shown only over the SAZ although it occurred globally. Finally, in **c**, GNAIW has replaced NADW, further slowing the ventilation rate of the abyss. This NADW-to-GNAIW switch should have focused the accumulation of dissolved inorganic carbon in the abyss and thus magnified the Southern-Ocean-driven deep sea $CaCO_3$ dissolution event that raised the pH of the ocean and thus further lowered $p_{CO_2}^{atm}$. Speculatively, **b** may represent a mid-glacial state (see text and Fig. 4).

Sigman et al. 2010

During Glaciated Times: Millenial Oscillations

• Occur throughout glaciated times, but are very muted in interglacial periods. So, we believe ice sheets must have been involved

•Dansgaard-Oeschger (DO) oscillations

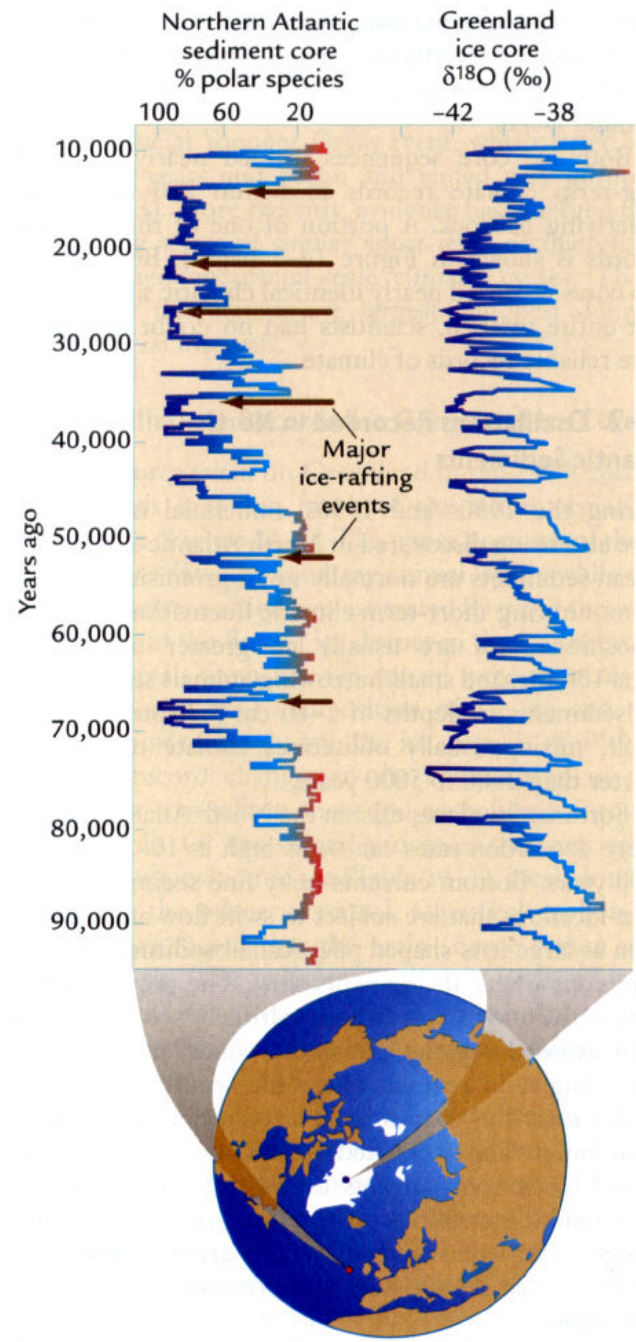
- Approx 1500 years

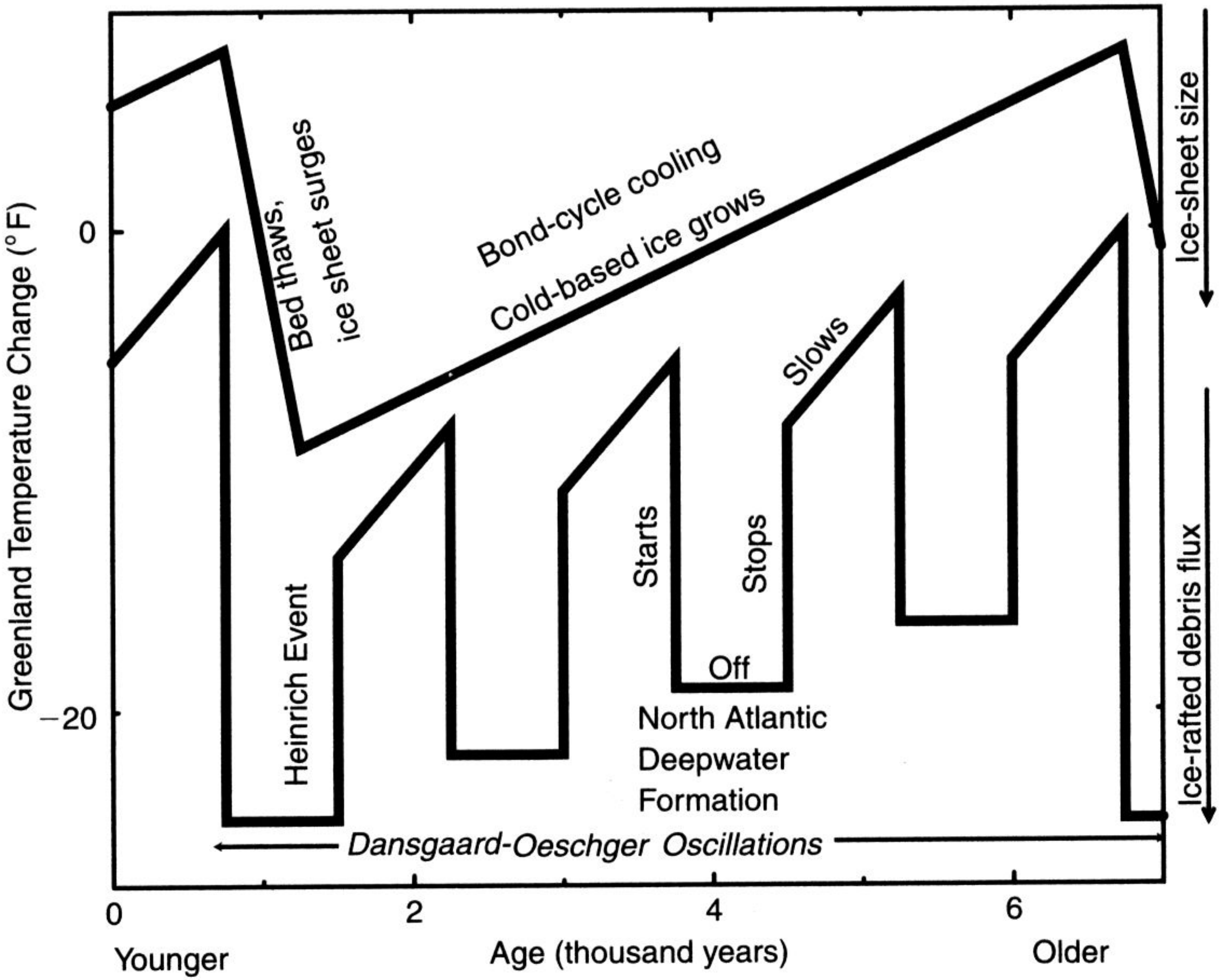
• Several DO oscillations terminate in a Heinrich event (indicated by ice-rafted debris found in N. Atlantic)

• The combined cycle is a "Bond Cycle"

• Irregular timing contrasts to orbital timescale variations on which these oscillations are imposed

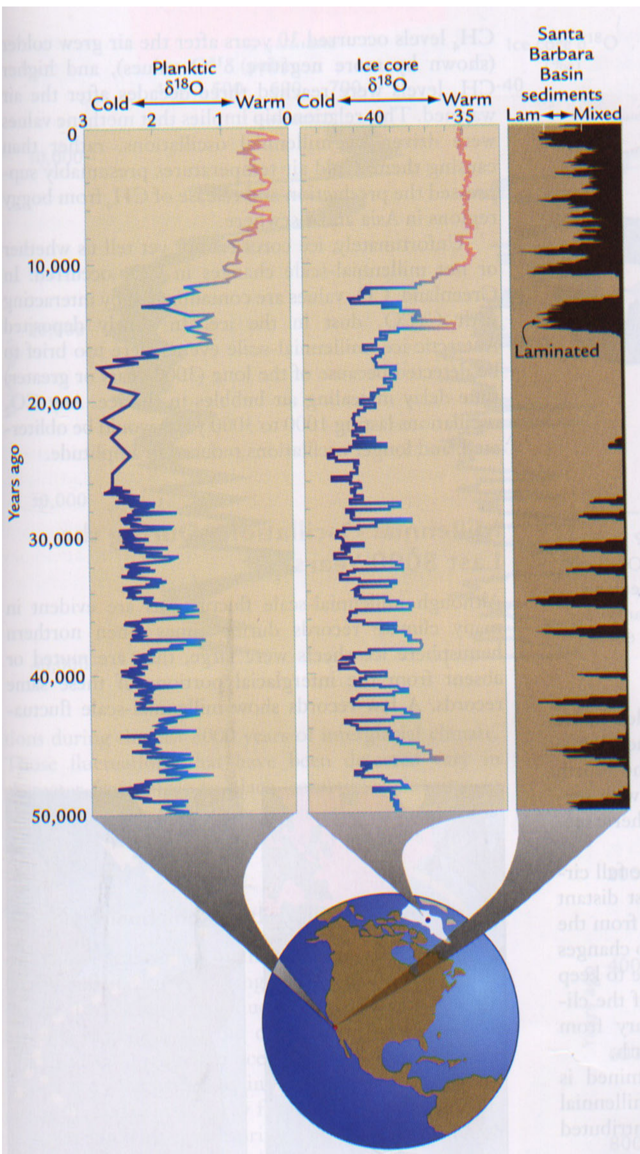
- Red noise of a random / staggering process?
- Problems with data interpretations / dating?
- Nonlinear instability in ice sheets?



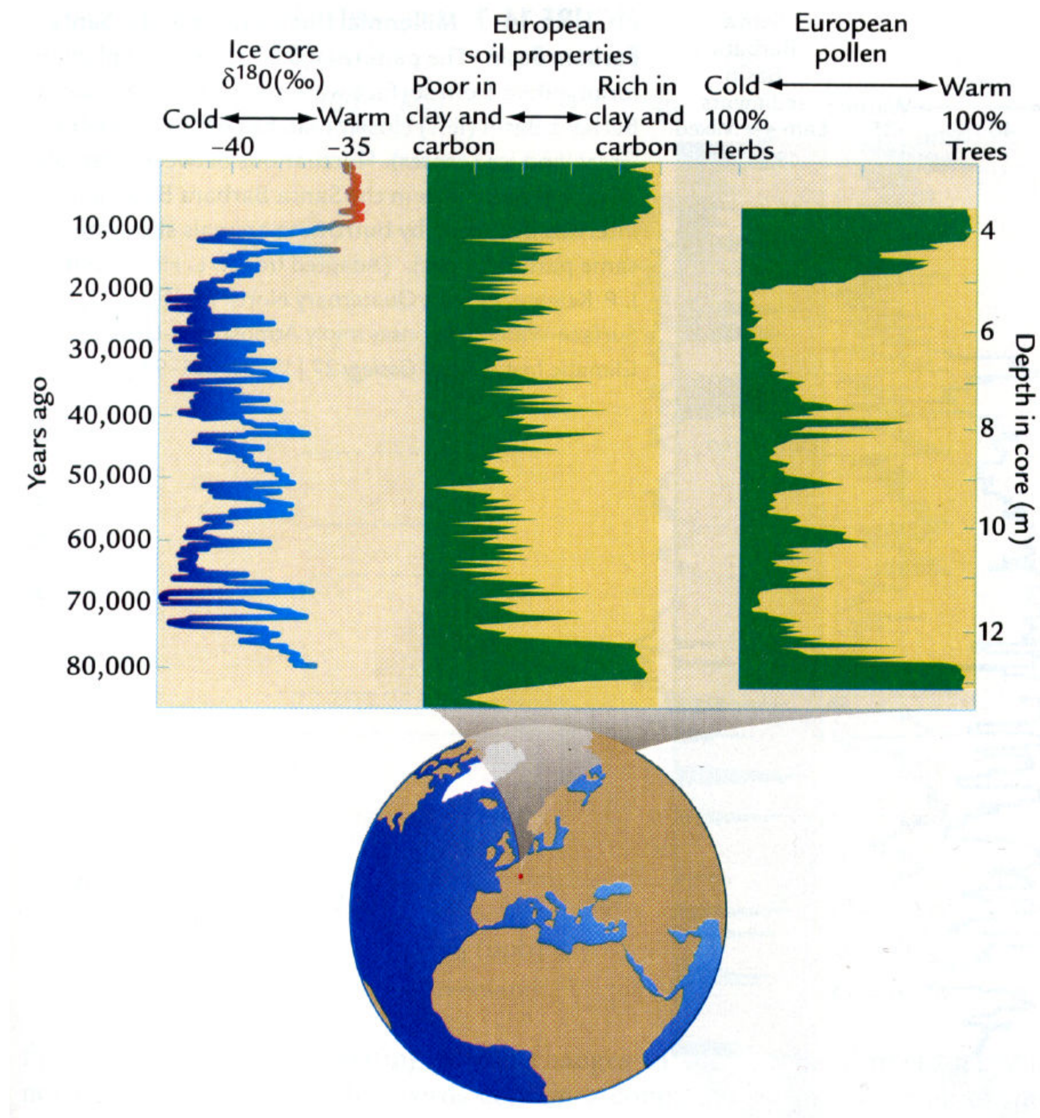


Alley, Two Mile Time Machine, Fig 12.4

Evidence in Santa Barbara



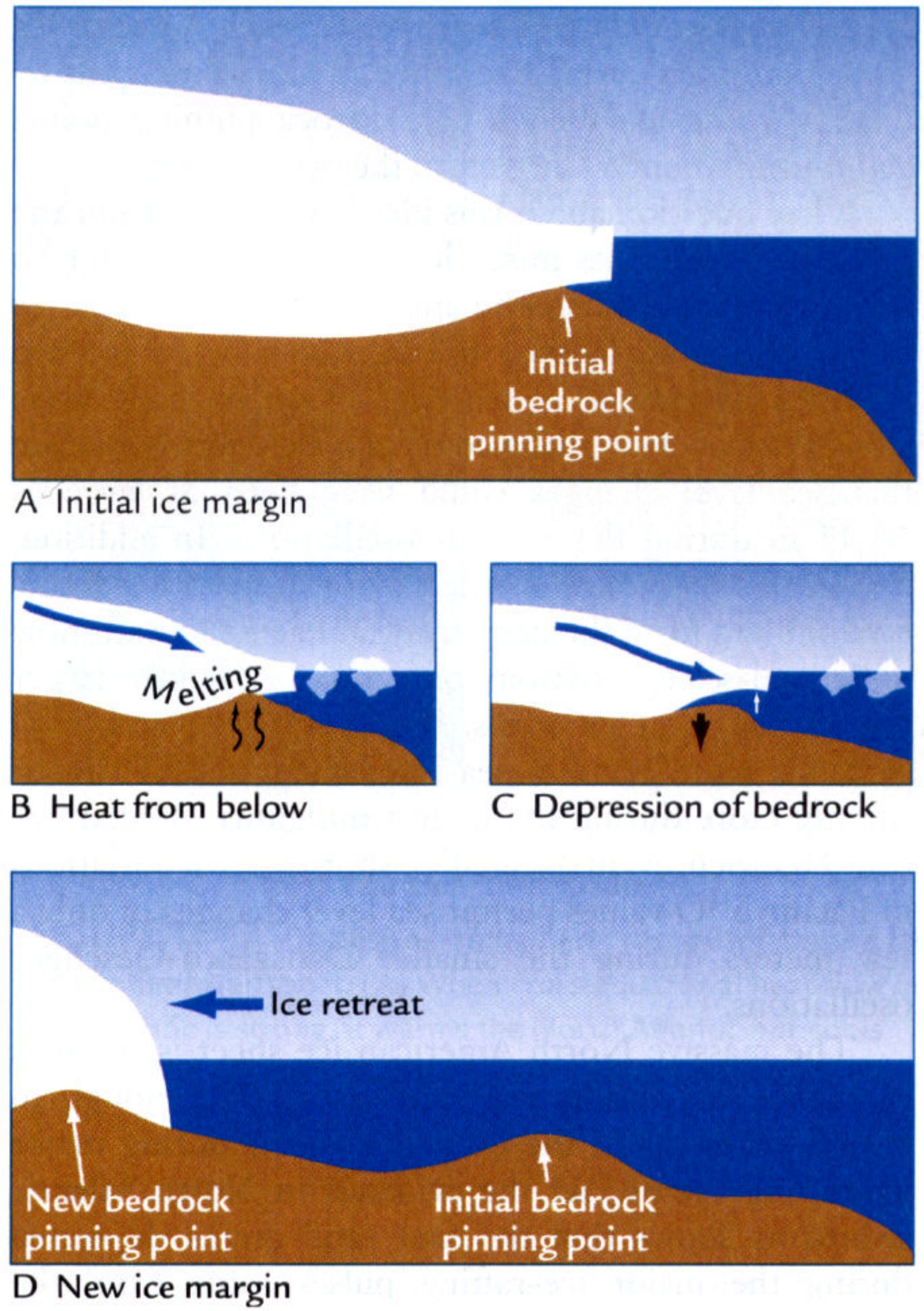
Evidence in Europe



Ice Sheet Instability?

- Did ice sheets become unstable as they grew to their largest extent?
  - Insulating the ground
  - Moving over softer bottom of Hudson Bay
- Could a massive breakdown lead to the observed changes?
  - Ice rafted debris signal
  - Initial cooling to North Atlantic
  - Then ice sheet stable and begins to grow again
- Sea level (10-15m changes) may link activity of separate ice sheets

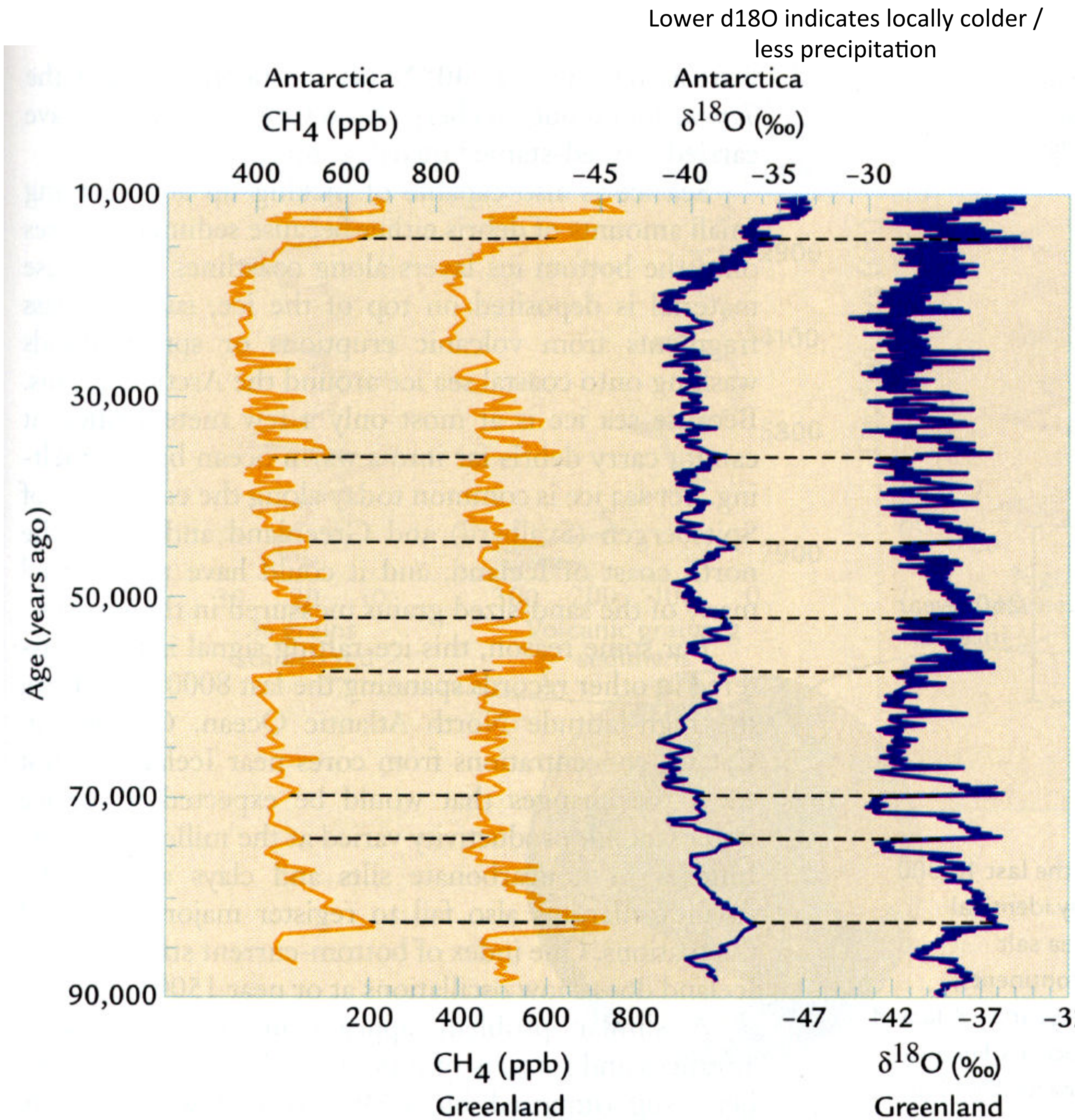
- How does ice surge and thermohaline circulation interact? Timing? Still to be resolved



Antarctica?

- By matching timeseries of CH4, can determine how the southern pole varied

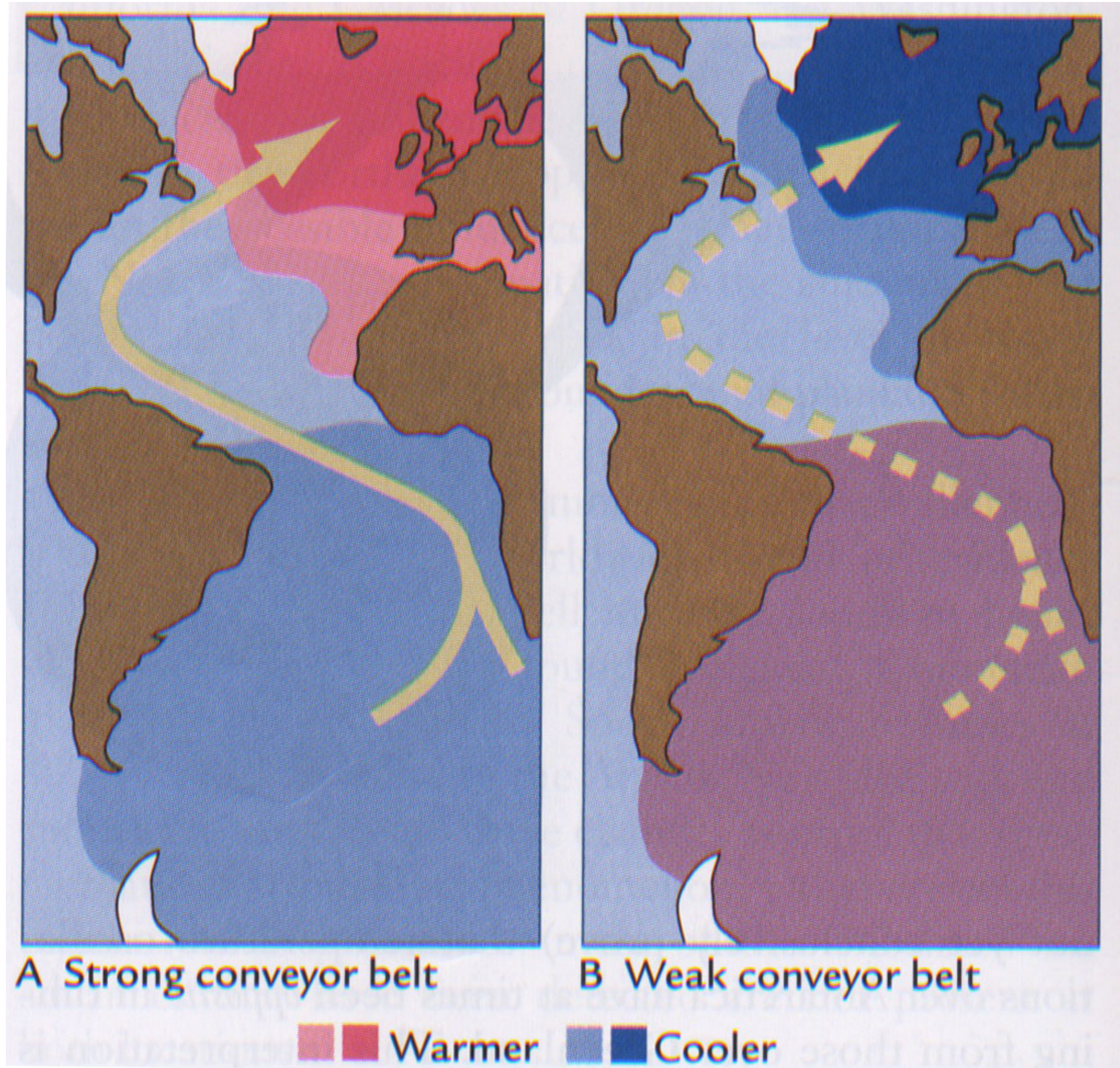
- Find that it was out of sync with the North



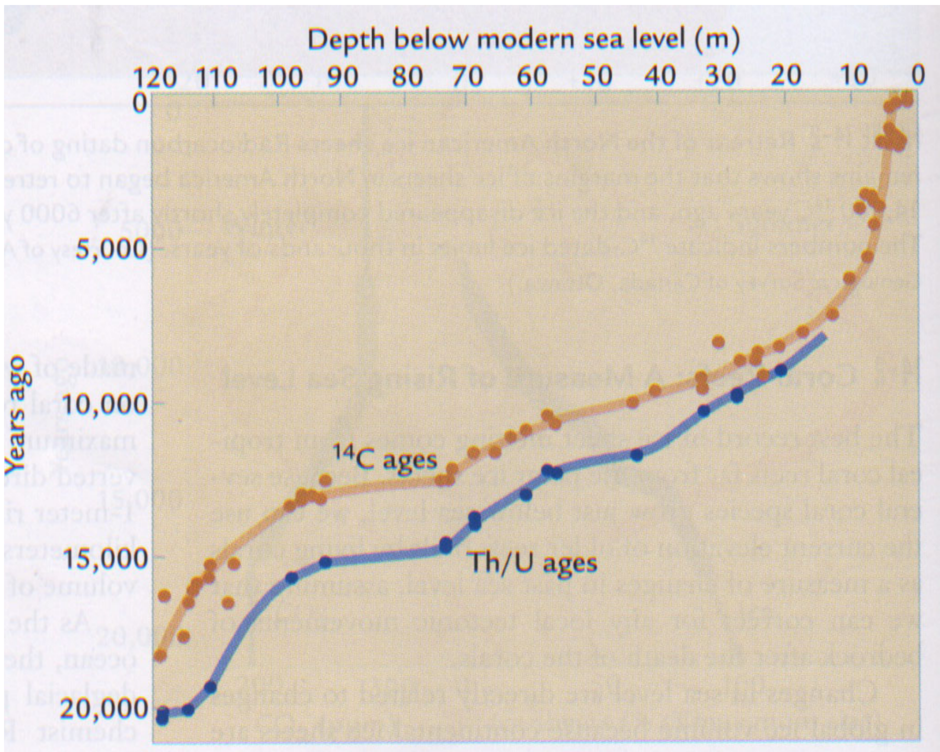
“Bipolar Seesaw”

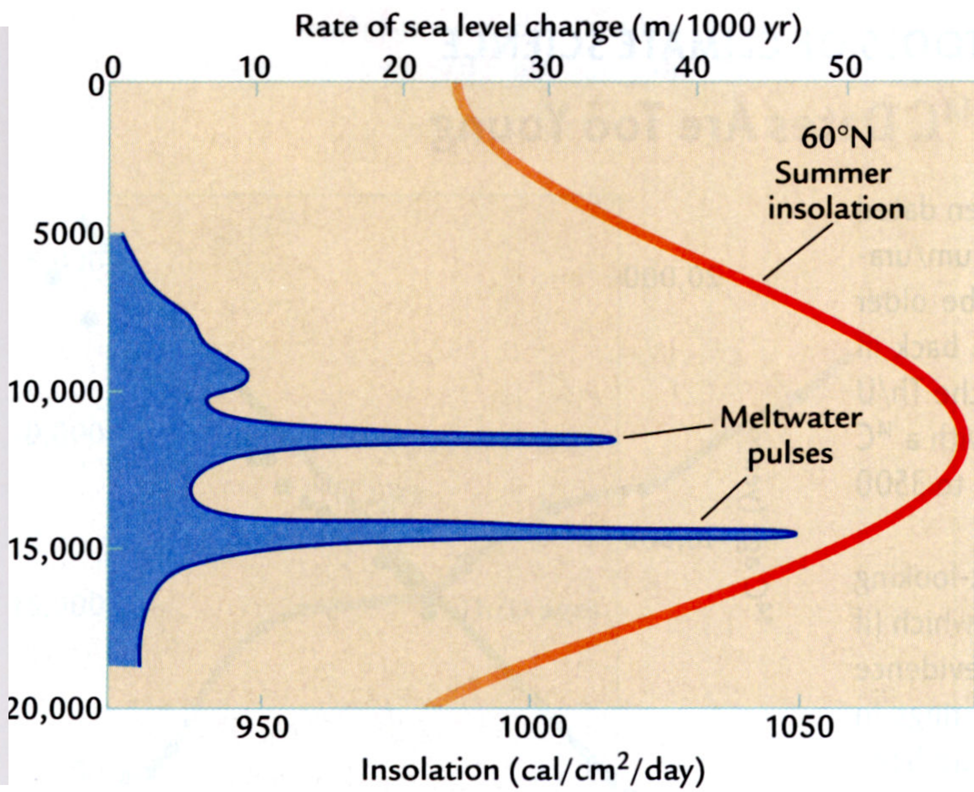
- Antarctica and Greenland oscillations are out of phase.
- The North Atlantic carries much heat South to North.
- Changes in this circulation could have modified both climates, with out of phase timing

- But what is the driver? Why would such a ‘seesaw’ occur? Not clear.



Deglaciation not a smooth process



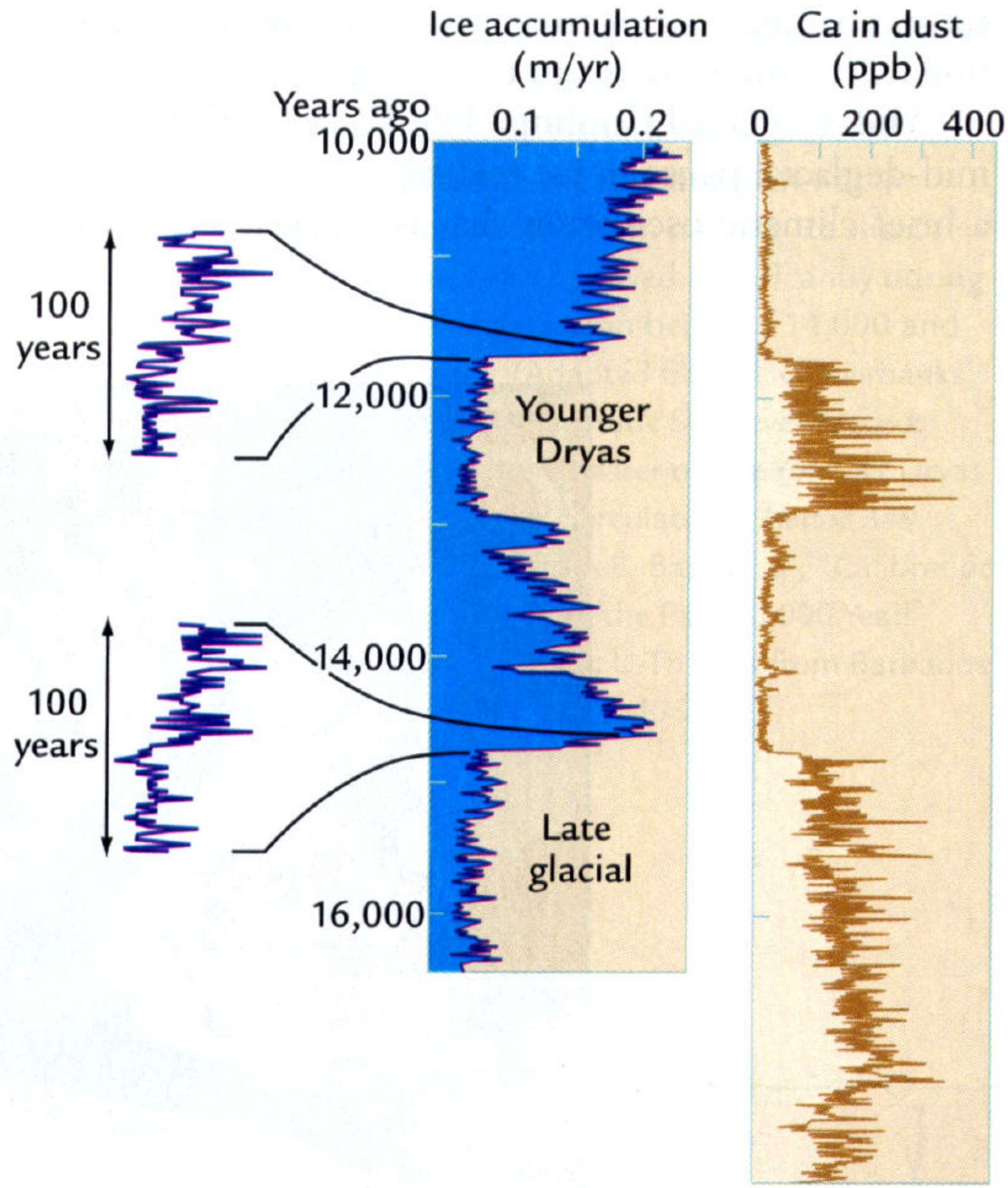


Younger Dryas

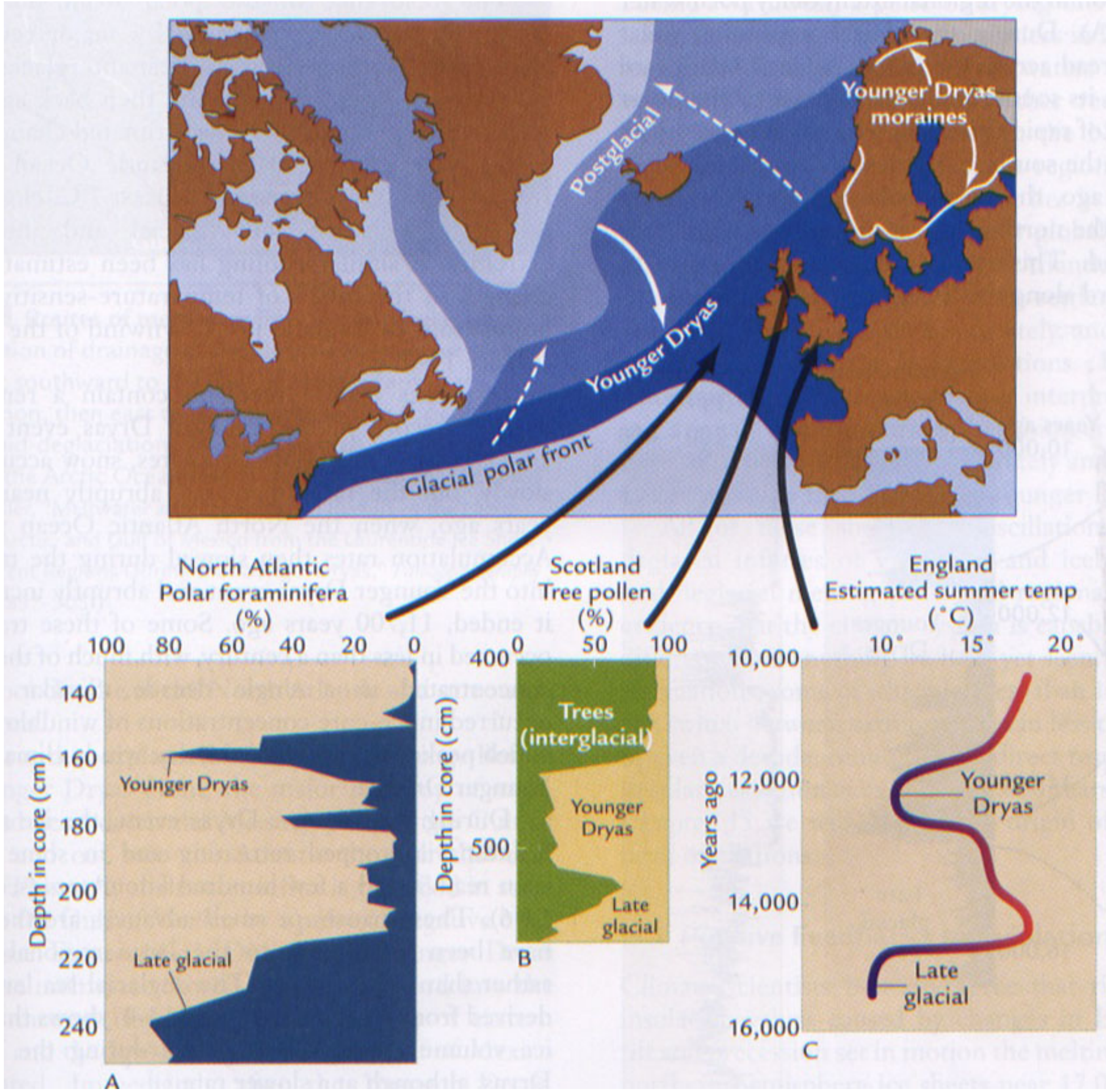
13,000 years ago, the warming paused for about 1200 year

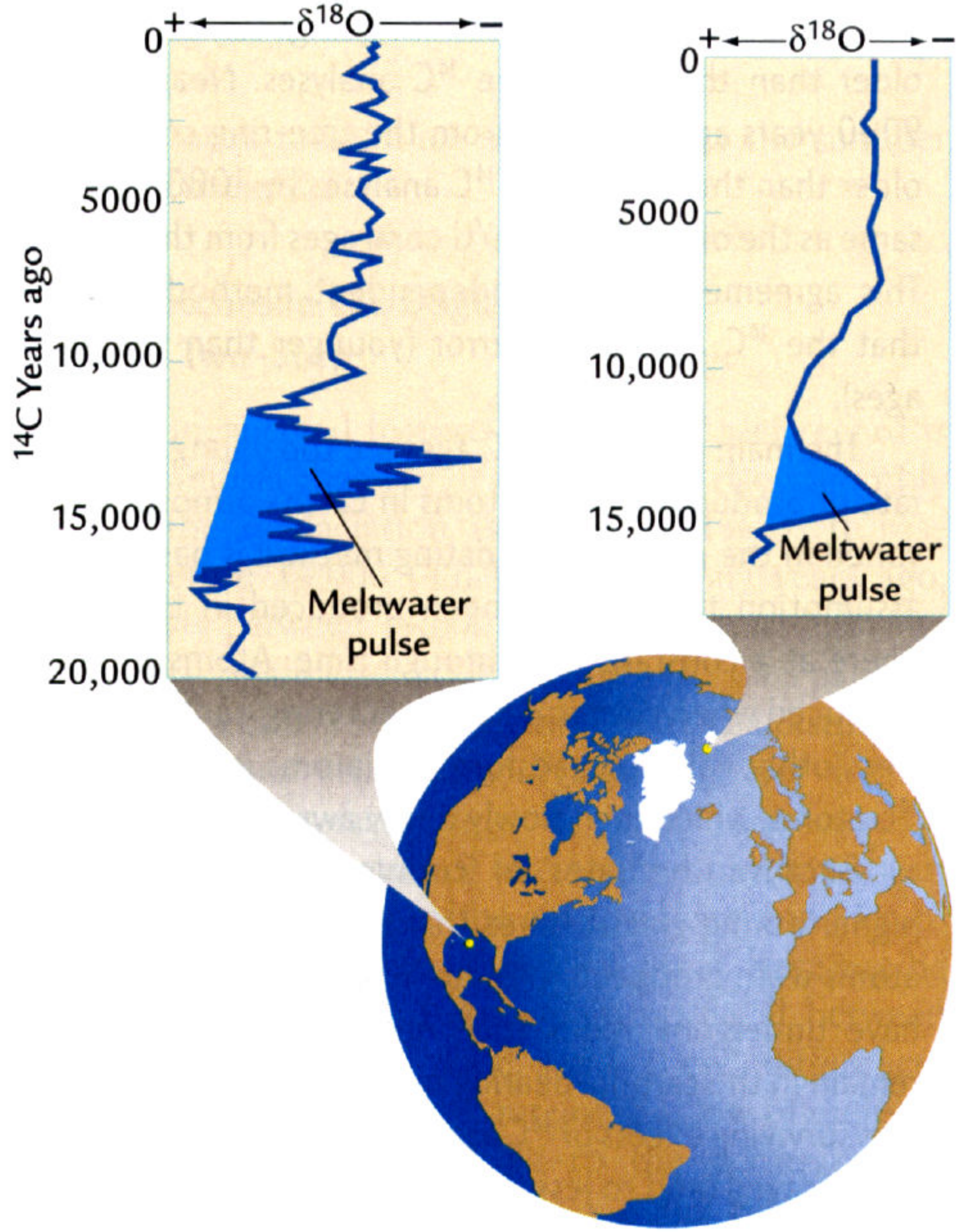
and then restarted abruptly in only 100 years

A dramatic return to glacial – like conditions



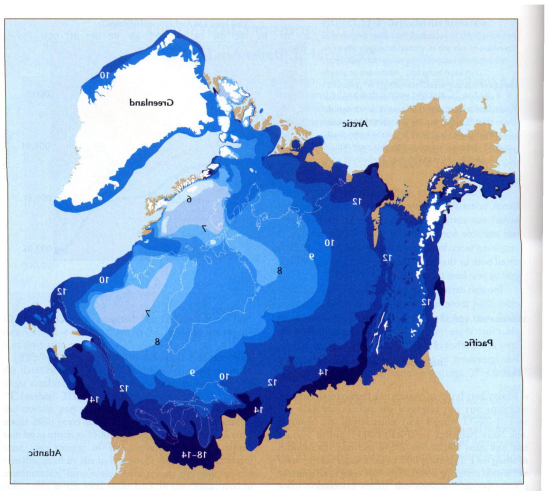
Younger Dryas



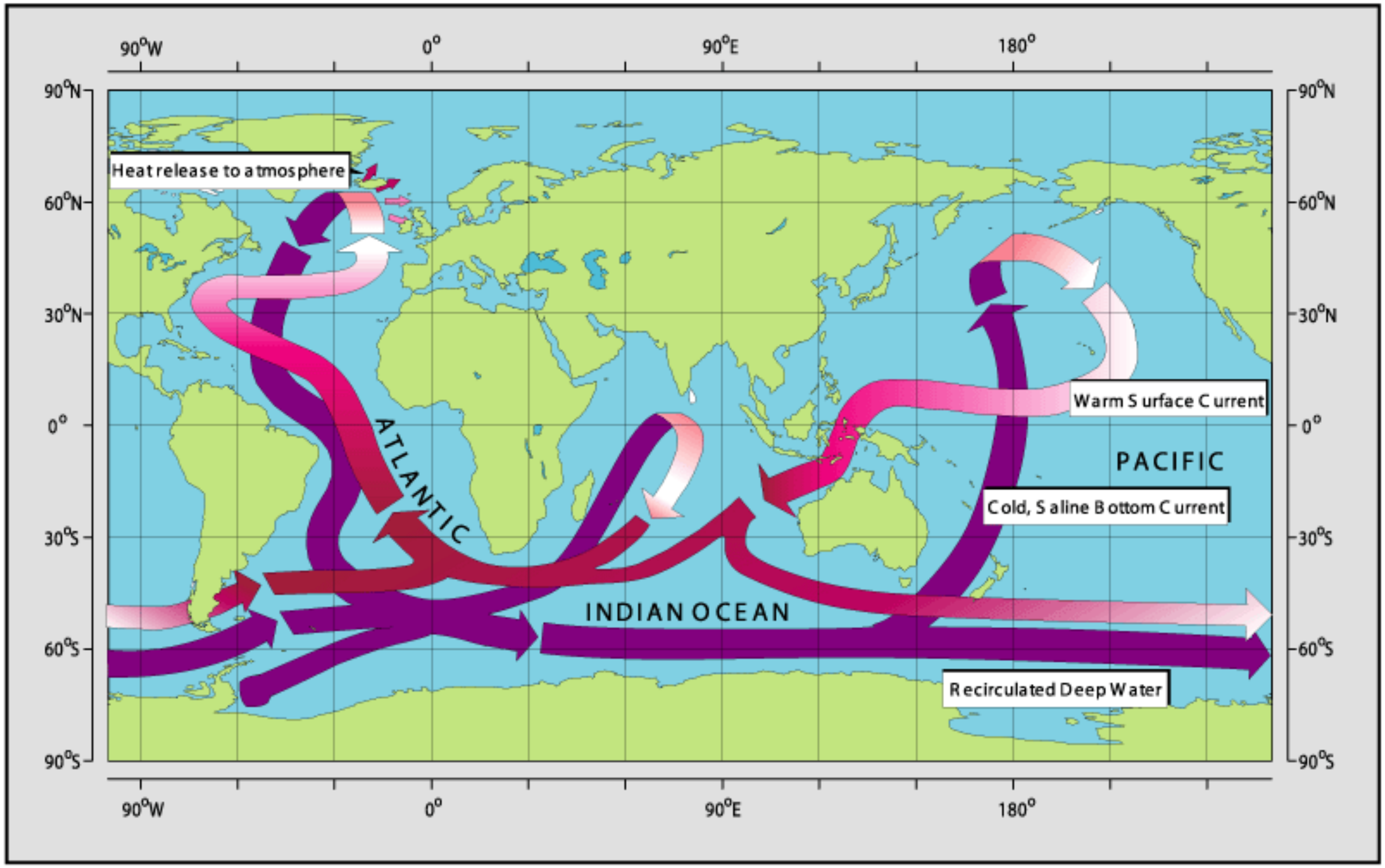


δ18O
0
5000
10,000
15,000
20,000
14C Years ago
Meltwater pulse
δ18O
0
5000
10,000
15,000
Meltwater pulse

Pathways for meltwater flow



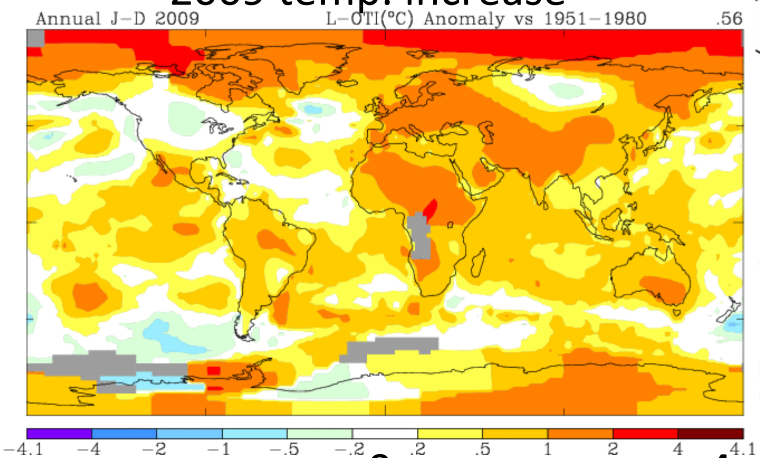
Thermohaline Circulation (simplified)



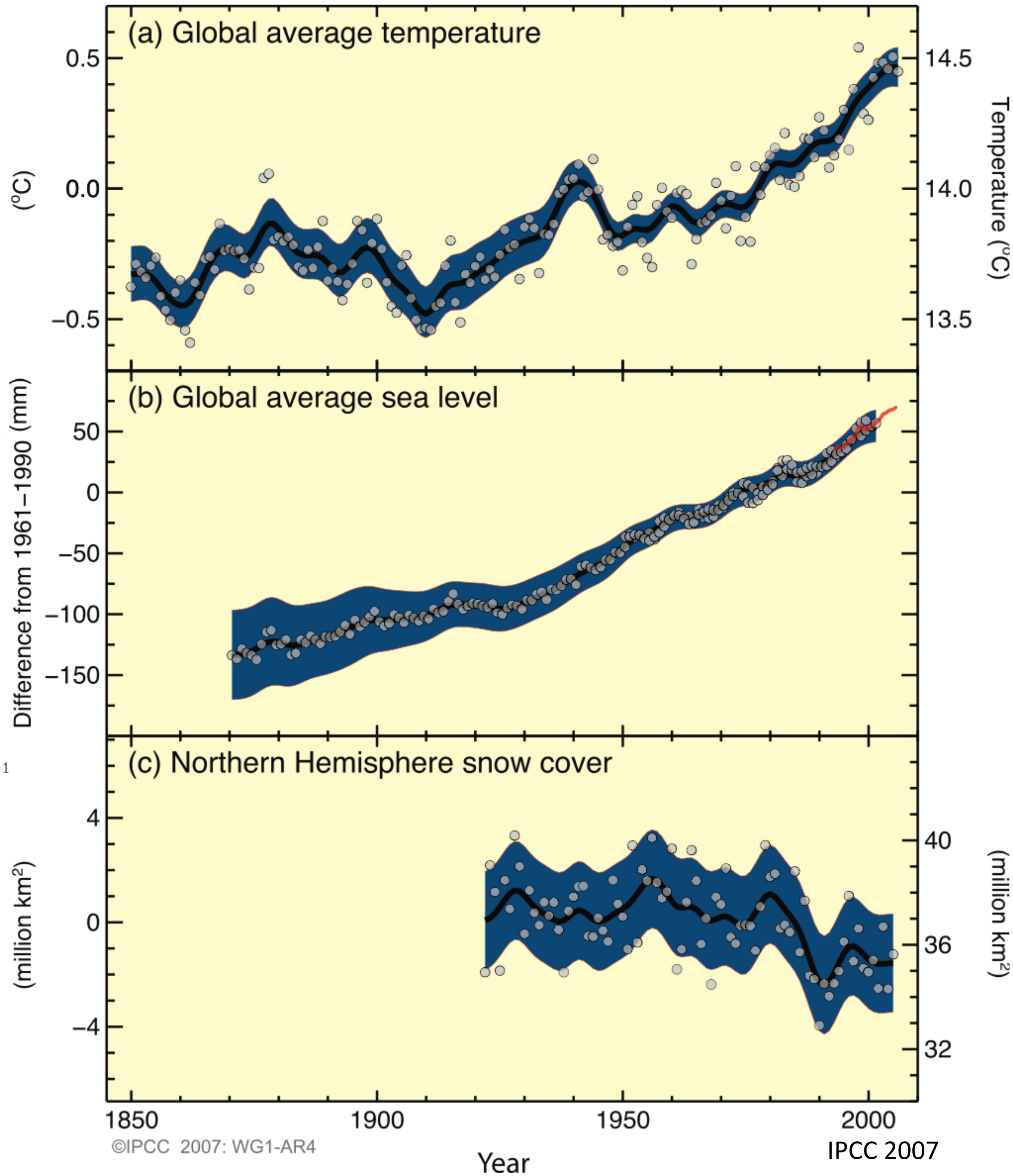
Clivar Science Figures

Now, climate is changing quickly

2009 temp. increase



NASA GISS

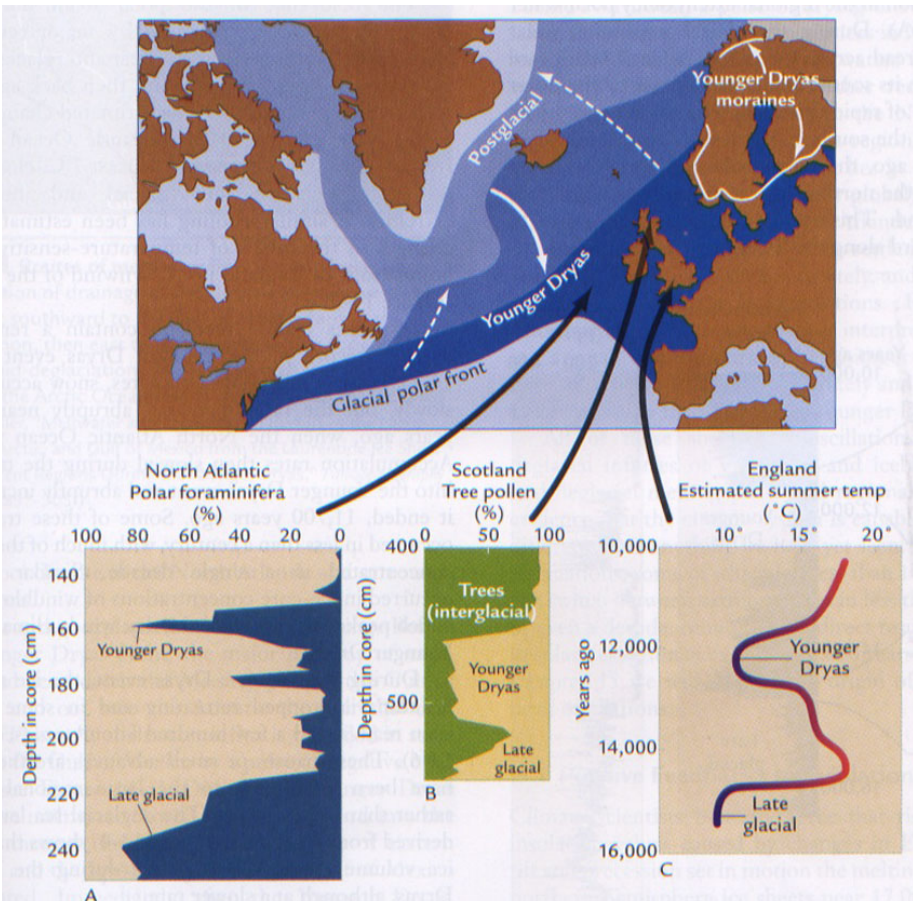


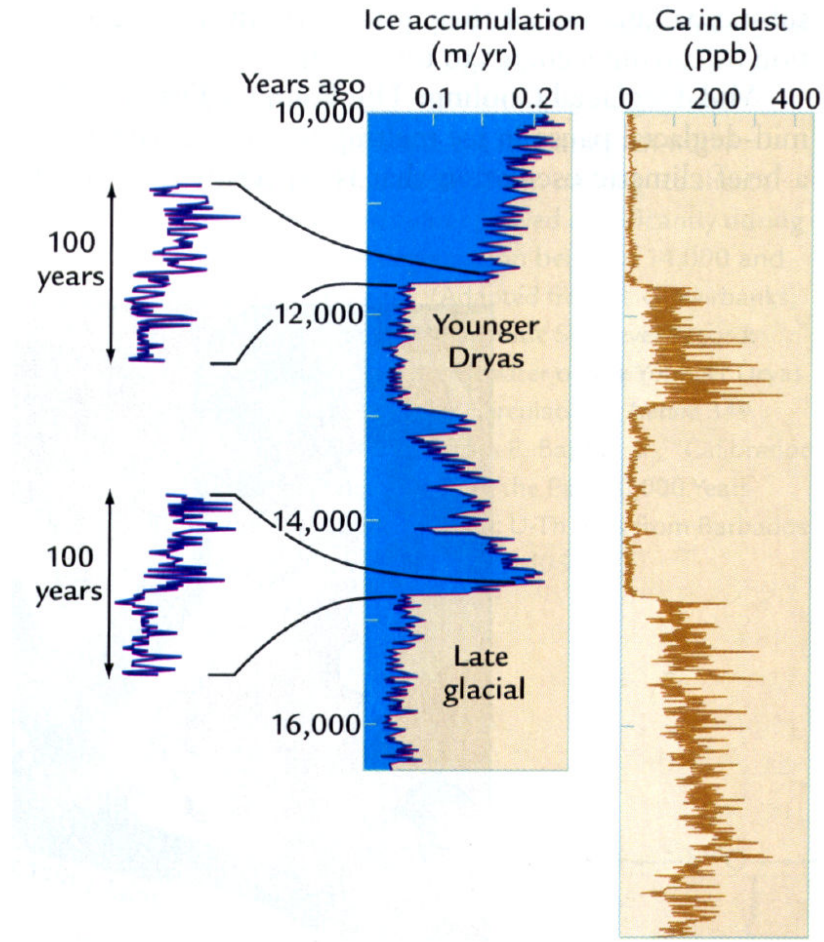
IPCC 2007

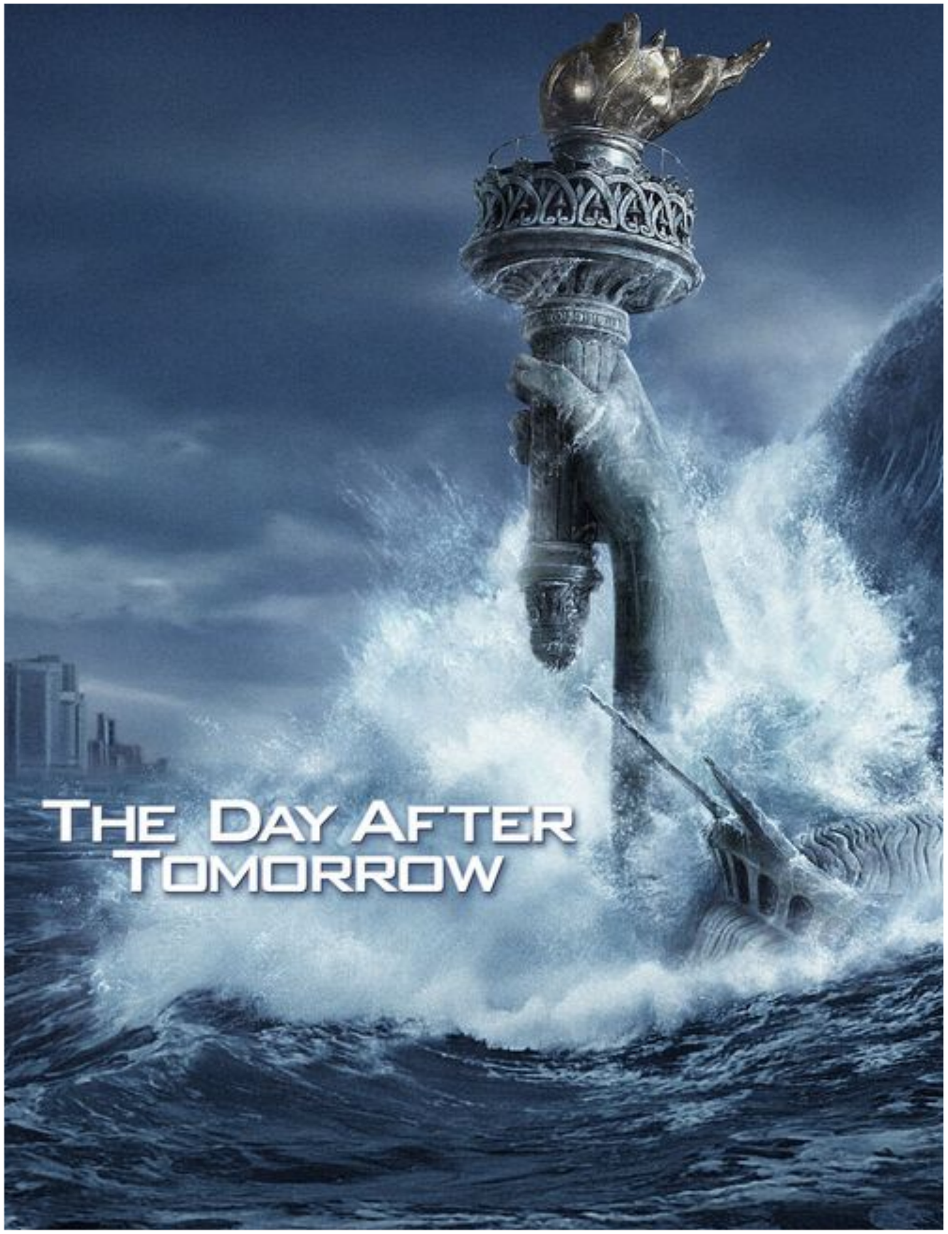
Greenland Ice Sheet is melting…

http://natgeotv.com/uk/extreme-ice/videos/greenland-ice-sheet

Will this lead to abrupt climate change?







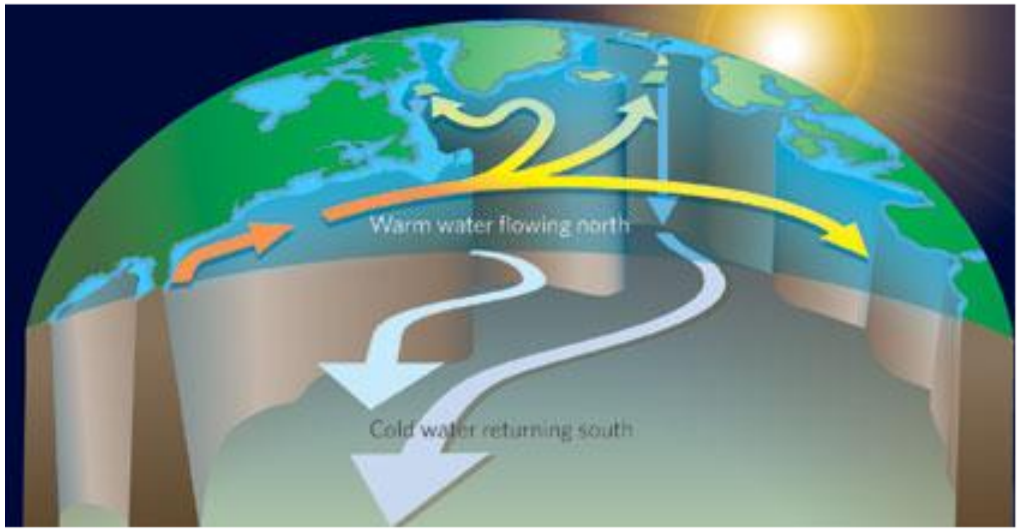
Or, cause an ice age!?

Leading scientists, such as Broecker, suggest motivation to limit global warming should come from the potential for abrupt change... He considers IPCC far too conservative.

But, can we observe a changing overturning and northward heat flux?

Slowing of the Atlantic meridional overturning circulation at 26.5°N

Bryden et al. 2005 (Nature)



"the Atlantic meridional overturning circulation has slowed by about 30 per cent between 1957 and 2004."

<u>22.9 Sv in 1957 to 14.8 Sv in 2004</u>

1 Sv = 10^6 m^3/s

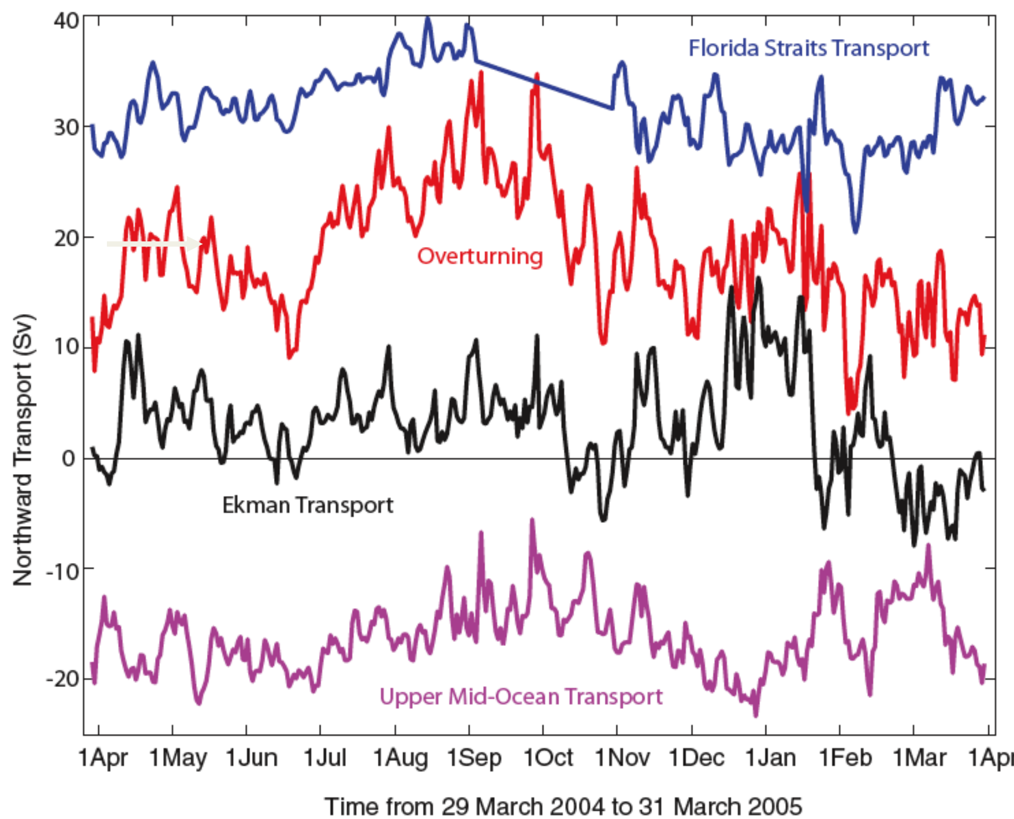
Temporal variability of the Atlantic Meridional Overturning Circulation at 26.5° N

Cunningham et al. 2007 (Nature)

Overturning varies from 4.0 to 34.9 Sv in 1 year

Previously-reported trends are not clear

Need 50 years of continuous observation to detect a trend



Conclusions

- The evidence is strong that the ocean plays a significant role in changing climate from glacial / interglacial cycles to shorter term oscillations
- Yet, the mechanisms of these effects are not fully understood
- Nor are observations sufficient to directly observe current change