12.842 / 12.301 Past and Present Climate
Fall 2008

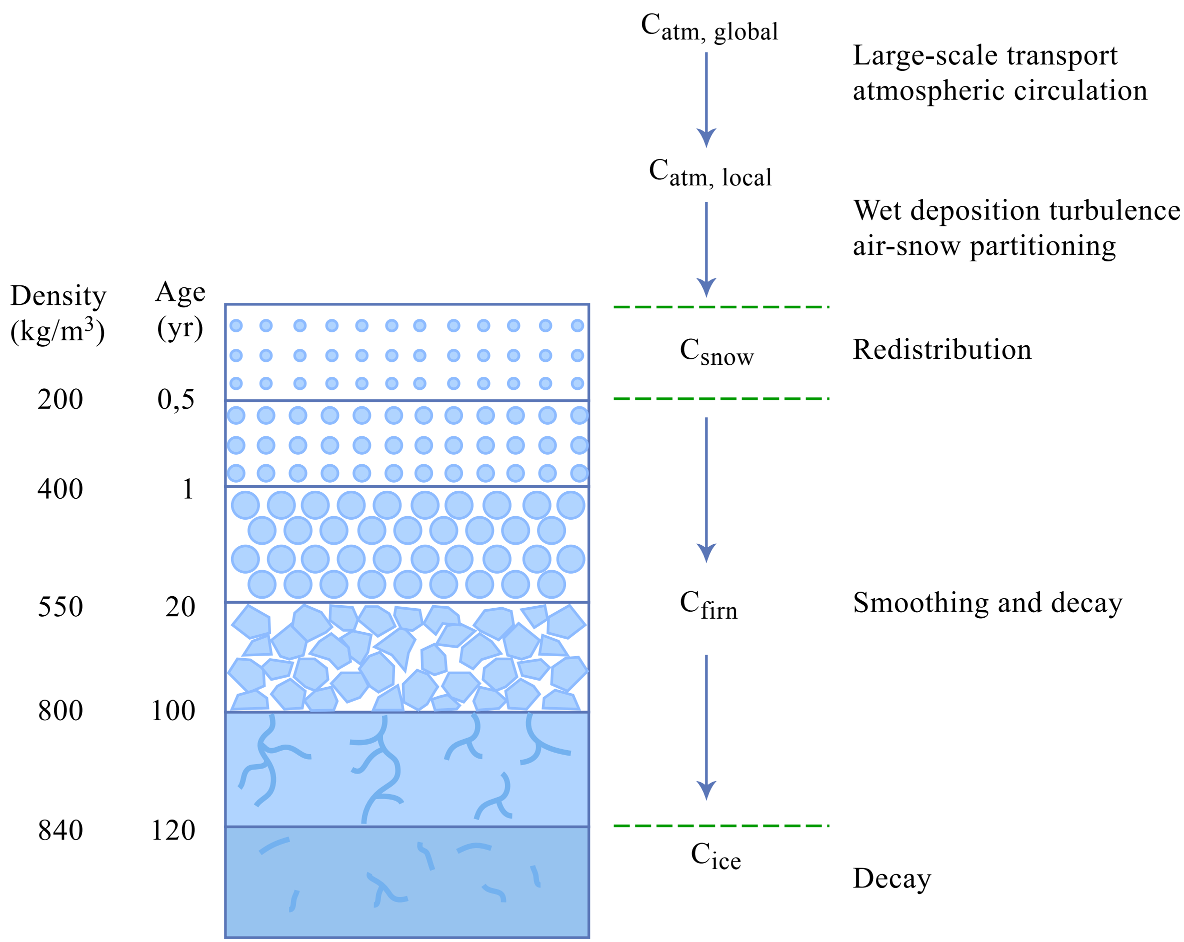
Ice Sheet Paleoclimatology

Climate Physics and Chemistry

12.842

Fall 2008

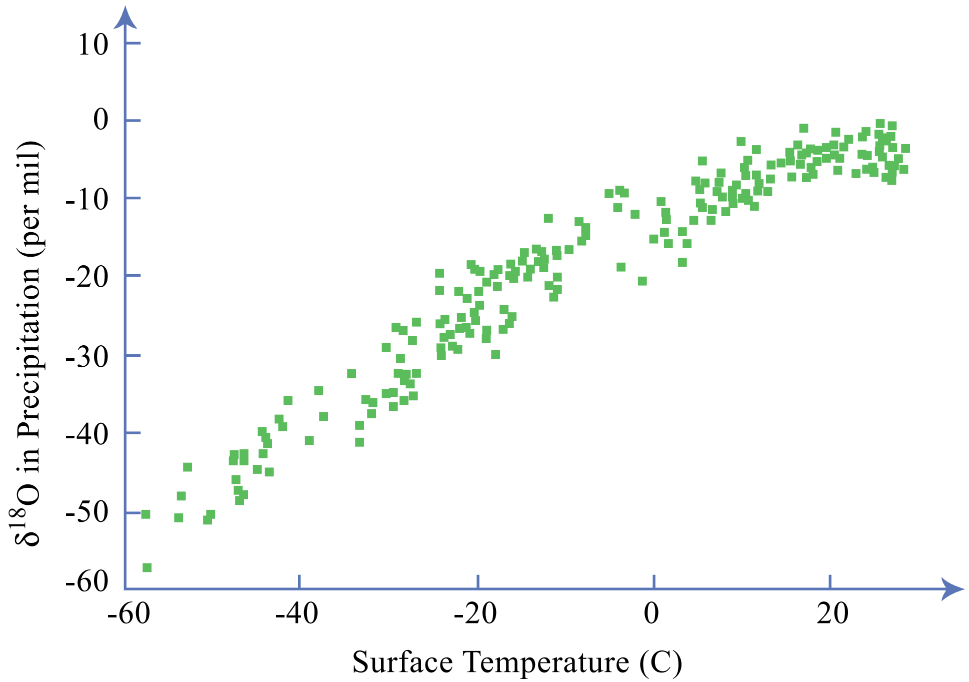
Transformation of snow into ice



Processes and steps involved in transfer function, which relates concentrations in ice to those in the global atmosphere. Depth and age scales are for Greenland. Snow-to-firn transition is defined by metamorphism and grain growth; firn-to-ice transition is defined by pore closure.

Figure by MIT OpenCourseWare based on Neftel, et al., 1995.

Observed $\delta^{18}O$ - surface temperature relationship



Observed $\delta^{18}O$ versus observed T (annual mean). The annual means for the IAEA [1981a] sites are computed from monthly means through precipitation weighting.

Figure by MIT OpenCourseWare based on Jouzel, et al., 1987.

Jouzel et al., 1987

Two ice cores from Antartica

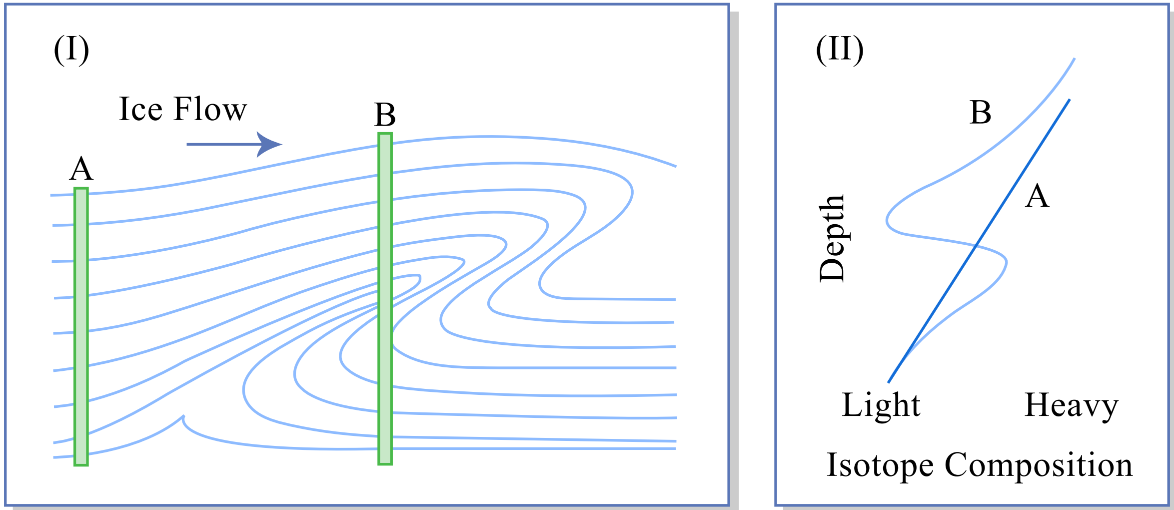
(and two sediment cores)

Image removed due to copyright restrictions.
Citation: Figure 2. *Nature* 429 (June 10, 2004): 624.

Two ice cores from central Greenland

Image removed due to copyright restrictions.
Citation: Grootes, P. M., Stuiver M., White J. W. C., Johnsen S., and Jouzel J. "Comparison of Oxygen Isotope Records from the GISP2 and GRIP Greenland Ice Cores." *Nature* 366 (1993): 552-554.

Folding near the base of the Greenland summit ice cores



I) A typical shear fold in the basal part of a glacier. If the ice had not been previously folded, a stratigraphic sequence of a climate-related property (such as oxygen isotope composition) sampled by a borehole at point A might produce a simple monotonic trend as shown by line A in part II. Sampling at B, after folding, would yield the sequence shown as B in II. Multiple folding can complicate the sequence further.

Figure by MIT OpenCourseWare. Adapted from Nature News and Views.

Abrupt climate swings during the past 100,000 years: the Bolling-Allerod, Younger Dryas, and “stadial/interstadial” “Dansgaard-Oeschger cycles

- Between 10,000-65,000 years ago, there were at least 17 abrupt swings between warmer and colder climate events.

- These events were first observed in the Greenland ice cores, but they have now been seen at diverse sites in the Northern Hemisphere including the tropics.

- These events are not observed in the Antarctic ice cores, save possibly in dampened form.

Image removed due to copyright restrictions.
Citation: Grootes, P. M., Stuiver M., White J. W. C., Johnsen S., and Jouzel J. “Comparison of Oxygen Isotope Records from the GISP2 and GRIP Greenland Ice Cores.” *Nature* 366 (1993): 552-554.

The Bolling/Allerod warming and Younger Dryas cooling

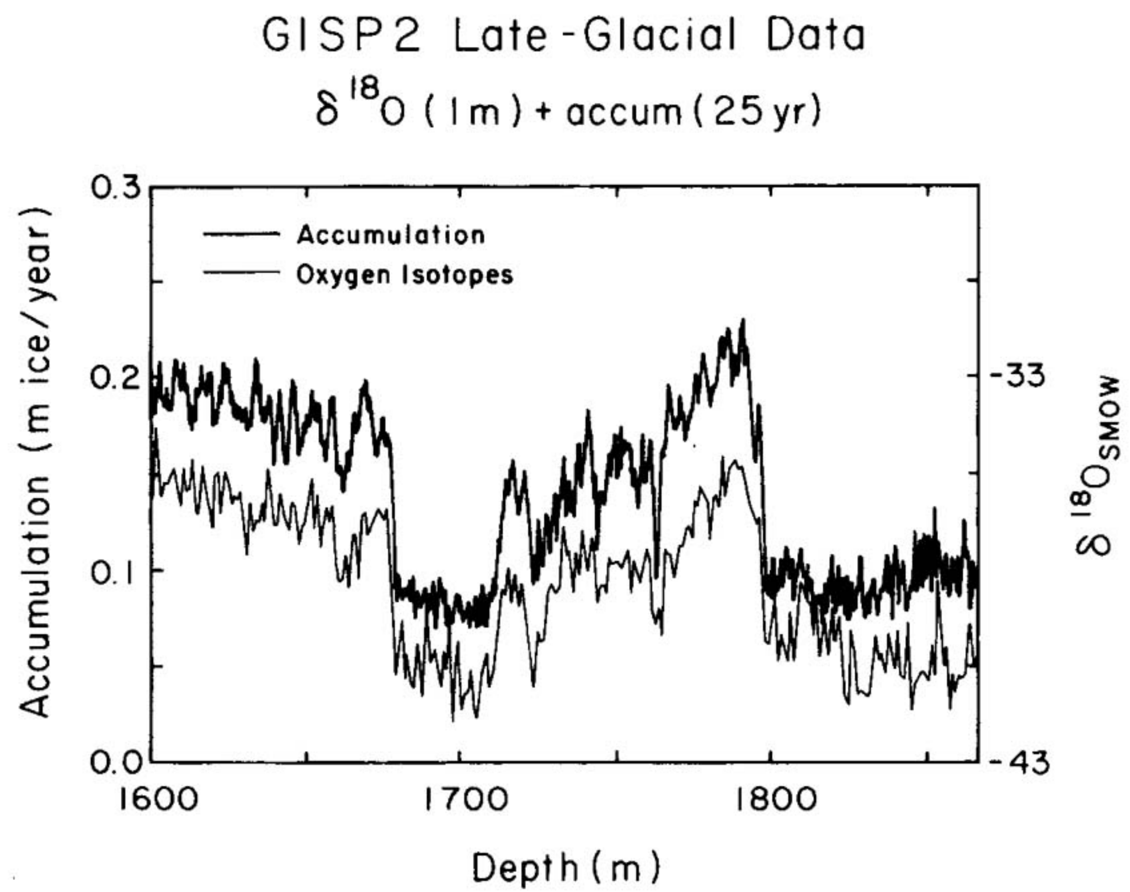


Figure 14. Annual accumulation rate (modified from Alley et al., 1993) and one meter average values for oxygen isotopes (Grootes et al., unpub.) plotted against depth. The cold periods (the Oldest Dryas below 1800 m, the Younger Dryas near 1700m and certain events during the Bolling/Allerod near 1750m) have low accumulation and the warm periods (most of the Bolling/Allerod and the Preboreal above 1670m) some of the changes such as the terminations of the Oldest Dryas and the Younger Dryas are very large and abrupt, indicating important reorganizations of the ocean-atmosphere system.

Figure from GISP2 Newsletter using data from M., Grootes P., Stuiver M., White J. W. C., Johnsen S., and Jouzel J. "Comparison of Oxygen Isotope Records from the GISP2 and GRIP Greenland Ice Cores." *Nature* 366 (1993): 552-554 and Alley, R. B., et al. *Nature* 362 (1993): 527-529.

Two ice cores from central Greenland

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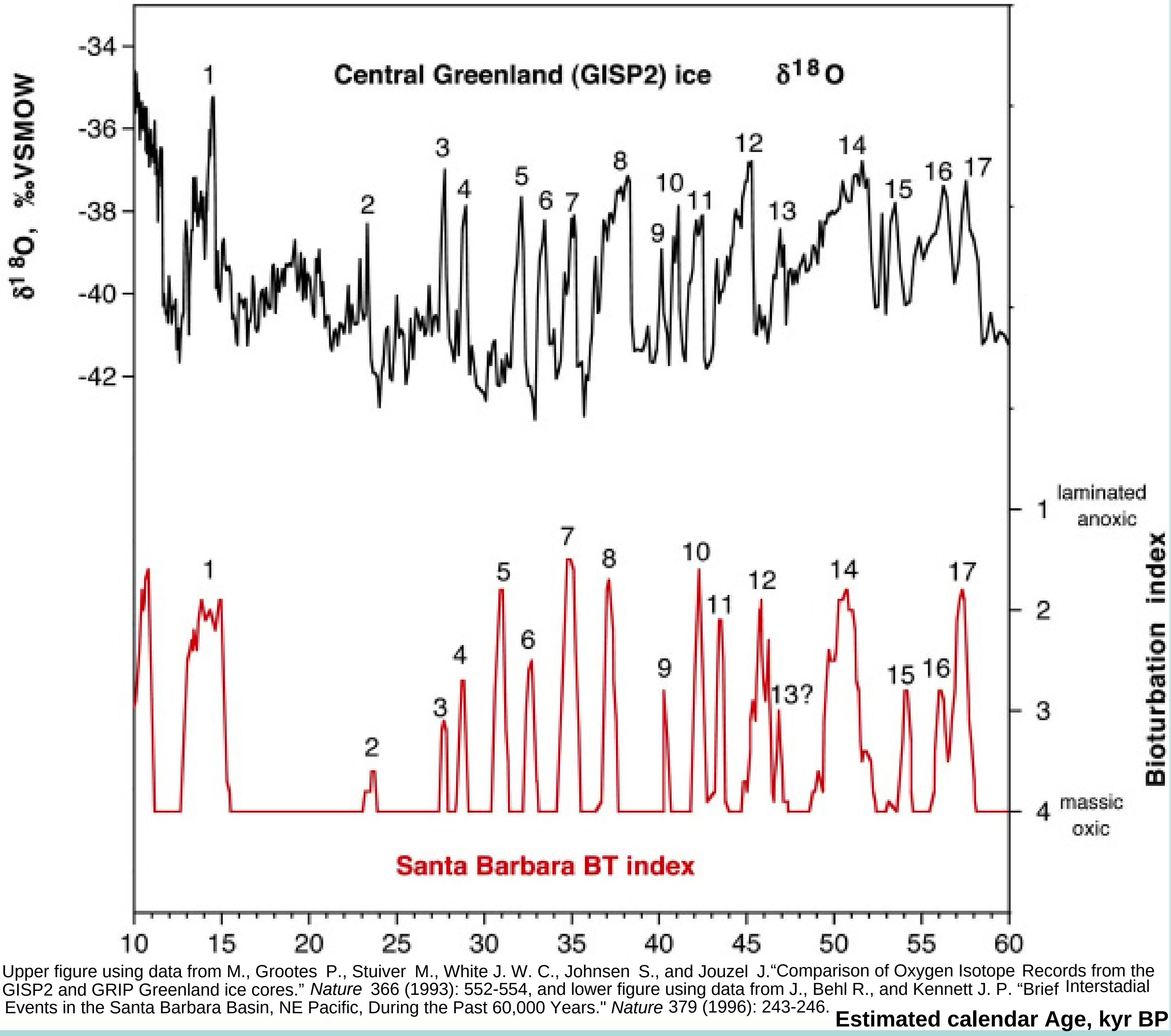
Citation: Grootes P. M., Stuiver M., White J. W. C., Johnsen S., and Jouzel J. "Comparison of Oxygen Isotope Records from the GISP2 and GRIP Greenland Ice Cores." *Nature* 366 (1993): 552-554.



Upper figure using data from M., Grootes P., Stuiver M., White J. W. C., Johnsen S., and Jouzel J."Comparison of Oxygen Isotope Records from the GISP2 and GRIP Greenland ice cores." *Nature* 366 (1993): 552-554, and lower figure using data from J., Behl R., and Kennett J. P. "Brief Interstadial Events in the Santa Barbara Basin, NE Pacific, During the Past 60,000 Years." *Nature* 379 (1996): 243-246.

Santa Barbara Basin

Speleothems: high resolution paleoclimate records from continental sites, with accurate Th/U dates

Image removed due to copyright restrictions.
Citation: Figure 1. *Science* 294 (2001): 2346.

“Heinrich Events”: sudden invasions of the North Atlantic by dirty icebergs

Image removed due to copyright restrictions.
Citation: Figure 3. Heinrich, H. “Origin and Consequences of Cyclic Ice Rafting in the Northeast Atlantic Ocean During the Past 130,000 Years.” *Quat Res* 29 (1988): 142-152.

Ice-Rafted Debris in North Atlantic Sediments

Heinrich Events: abrupt invasions of debris-bearing icebergs into the Atlantic Ocean

Sand-size (>150 μm) fraction in NW Atlantic Core
(foraminifera)

Sand fraction in HL-2 in NW Atlantic (670-672 cm)
Ice-Rafted Debris

Jennings *et al*. (1996)

Two ice cores from central Greenland

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Citation: Grootes, P. M., Stuiver M., White J. W. C., Johnsen S., and Jouzel J.
"Comparison of Oxygen Isotope Records from the GISP2 and GRIP Greenland Ice Cores."
Nature 366 (1993): 552-554.

Gases in Ice Cores

- Bubbles seal off at the bottom of the firn layer, ~80-120 m
- Hence gas is younger than the solid ice that contains it - the "gas age/ice age difference" depends on the accumulation rate
- Most gases are well mixed in atmosphere; so records from Antarctic and Greenland are nearly the same; features of the records can be used to correlate chronologies between hemispheres
- Gases that have been measured:
  - CO_2
  - O_2 ($^{18}O/^{16}O$ ratio)
  - CH_4
  - N_2O

CO_2 During the last 450 kyr from the Vostok, Antarctica Ice Core

Image removed due to copyright restrictions.
Citation: See image in Petit, et al. (1999) in Kump (2002) *Nature* 419: 188-190.

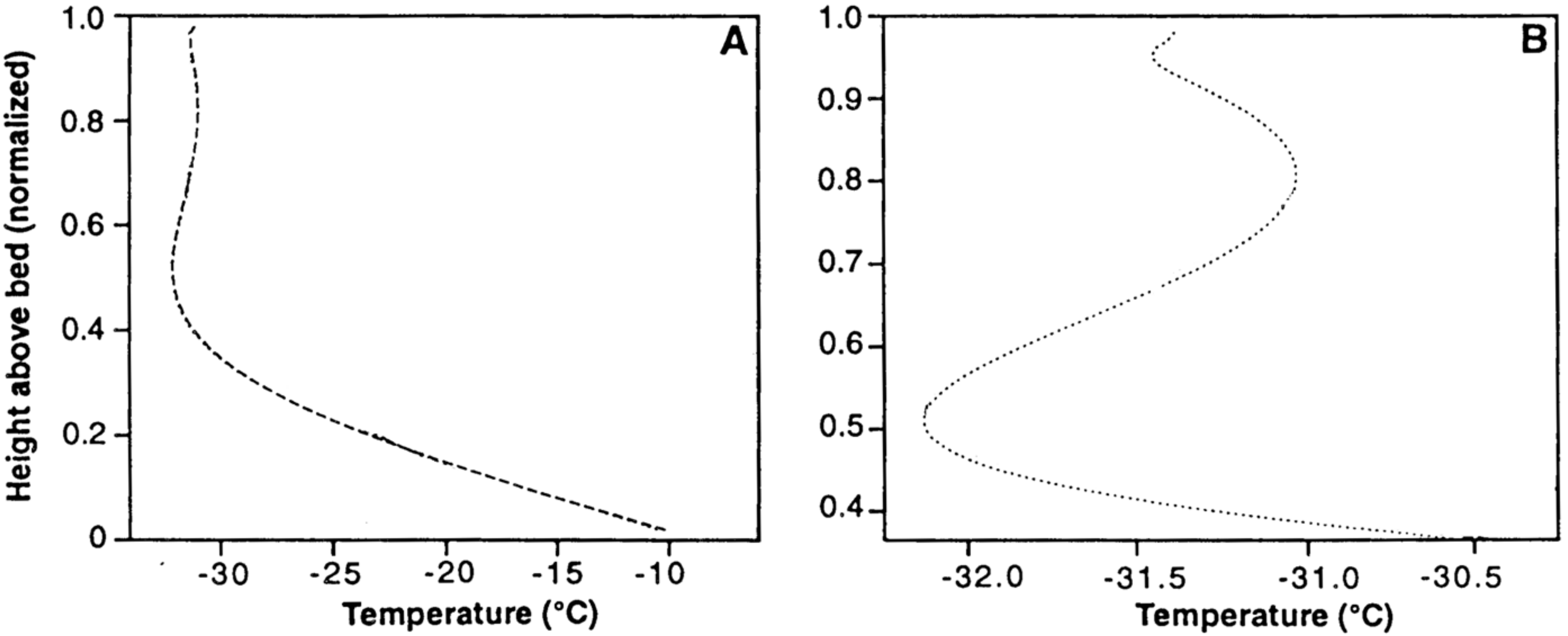
Image removed due to copyright restrictions.
Citation: Figure 1. Blunier, T., and E. Brook. “Timing of Millennial-scale Climate Change in Antarctica and Greenland During the Last Glacial Period.” *Science* 291 (2001): 109-112.

$\delta^{18}O$ and CH_4 in Greenland and Antarctica

Relic paleotemperatures from borehole temperatures

- Because heat diffuses through ice at a limited rate, the interior of the ice sheets is still colder than at the surface, a relic of last glacial maximum cold conditions.
- Given an accurate model of advection and diffusion, one can estimate what the original temperature was from a model.
- Time resolution becomes poorer further back in time (diffusional smoothing).

Borehole temperature profiles in central Greenland



GRIP borehole temperature Monte-Carlo inversions

Citation: Figure 3. "The Contour Plots of all the GRIP Temperature Histograms as a Function of Time." *Science* 282 (October 9, 1998): 270.

Borehole inversions imply that Greenland summit LGM temperature was -15°C colder than at present - twice the difference predicted from $\delta^{18}O$.

Why?

- Was the slope of the $\delta^{18}O$-T relationship 0.45 rather than 0.65? (Why?)
- Did the $\delta^{18}O$ relationship retain the same slope but shift its intercept? (This would be expected if source water temperatures were colder.)
- Did snowfall not accumulate in central Greenland in winter during the LGM? (If so, then the $\delta^{18}O$ of the ice only reflects the summer temperatures; this suggestion, supported by a GCM model, is taken as a result that very cold temperatures limit the amount of snowfall.)