Ice Sheet Paleoclimatology

Climate Physics and Chemistry

12.842

Fall 2008

Some images have been removed in this lecture notes due to copyright restrictions.
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.

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.
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 1700 m and certain events during the Bolling/Allerod near 1750 m) have low accumulation and the warm periods (most of the Bolling/Allerod and the Preboreal above 1670 m) 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.

Two ice cores from central Greenland

Image removed due to copyright restrictions.
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

Image removed due to copyright restrictions.

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$_2$O
CO$_2$ During the last 450 kyr from the Vostok, Antarctica Ice Core

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.
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
Image removed due to copyright restrictions.
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.)