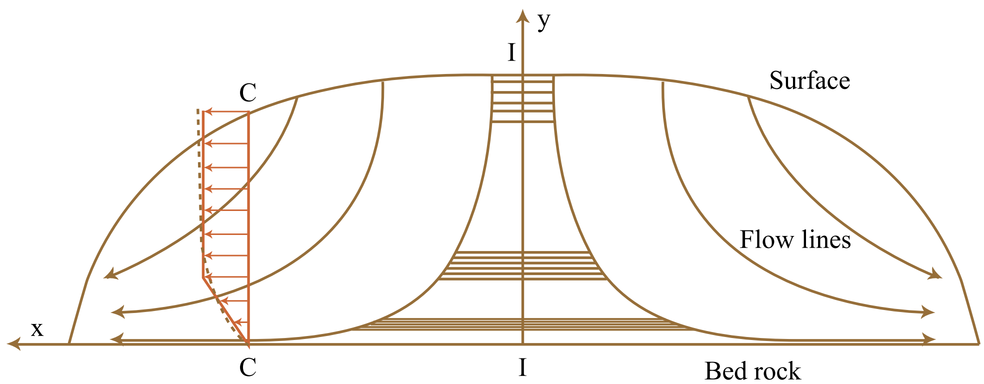
12.740 Paleoceanography
Spring 2008

Ice core evidence for climate change

I. Polar ice caps: characteristics and flow behavior



Vertical cross section of an ice sheet resting on a horizontal subsurface. Ice particles deposited on the snow surface will follow lines that travel closer to the base the farther inland the site deposition. An ice mass formed around the divide (I-I) will be plastically deformed (thinned) with depth as suggested by the lined areas. The dashed curve along the vertical ice core (C-C) shows the calculated horizontal velocity profile V_x (Weertman 1968b). The horizontal arrows along C-C show the adopted approximation to V_x (Dansgaard et al. 1969).

Figure by MIT OpenCourseWare. Adapted from source: Dansgaard et al. (1971).

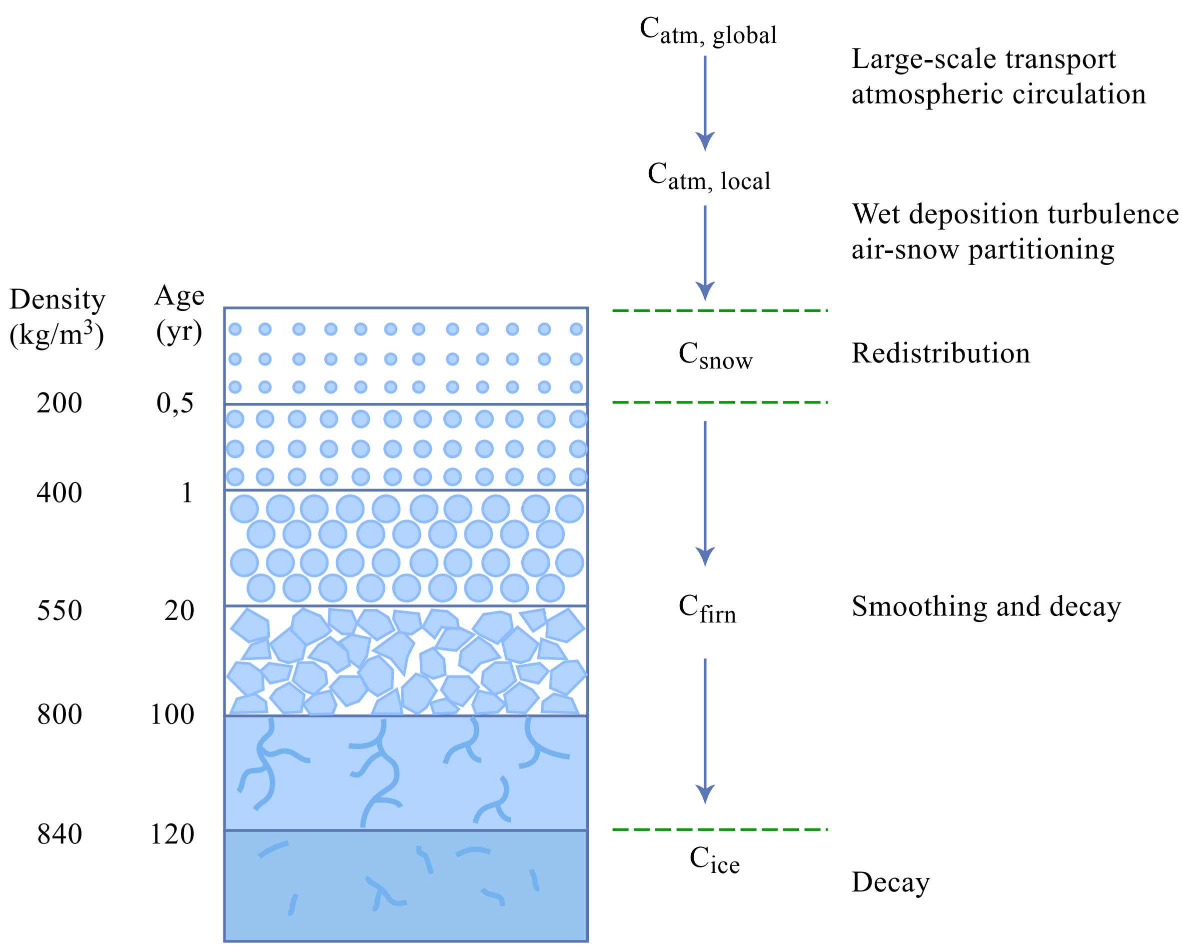
Note: this figure does not illustrate bedrock depression

A. Total ice mass on earth today: 29 x 10^6 km^3, equivalent to ~80m of sea level rise (but some of this would fill in space filled by sub sea-surface ice)..

B. Physical Properties and Transitions

1. Depth transitions

   a. Snow-->firn-->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.

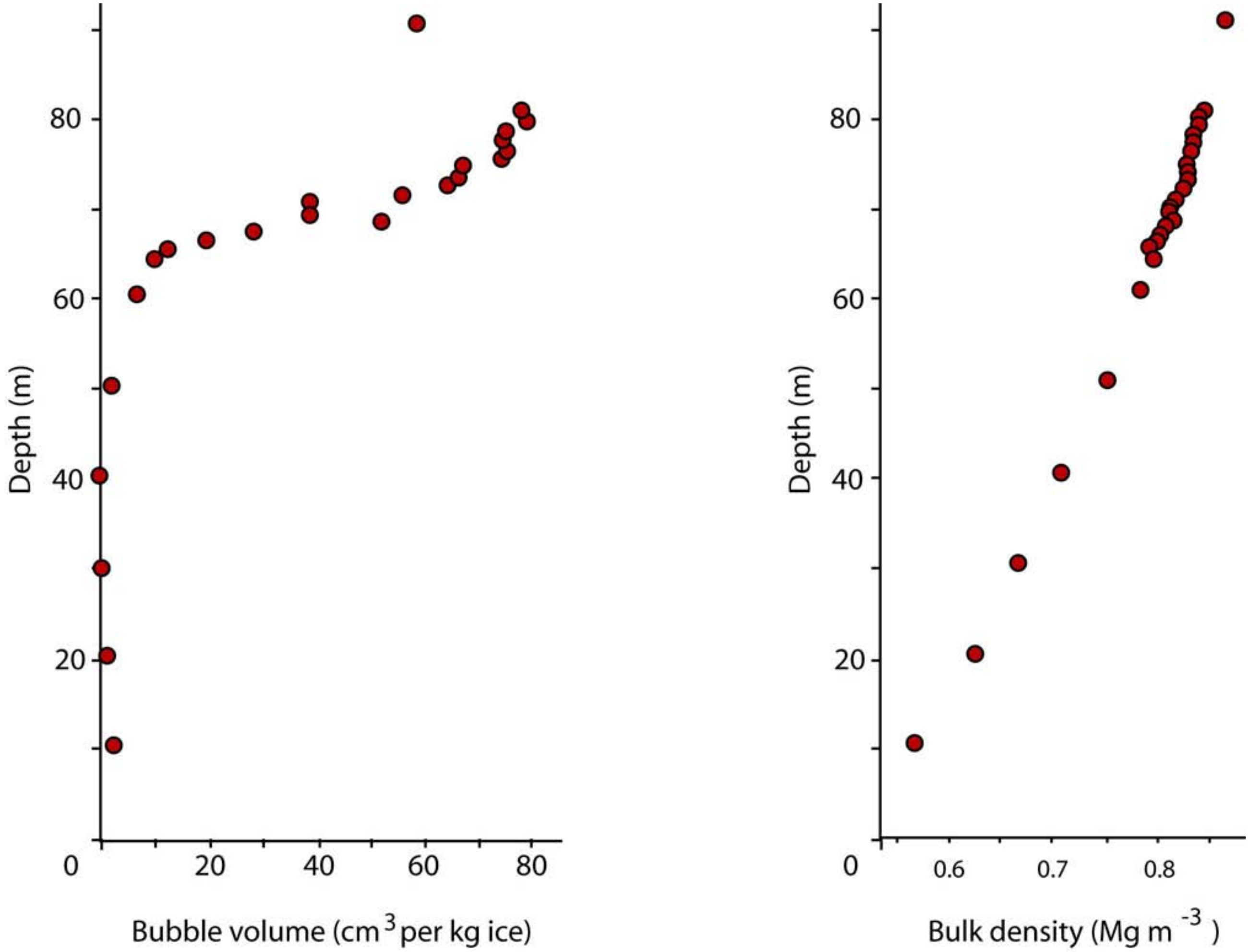
b. Bubble closure and compression: appearance of air hydrate inclusions 1000-1300m; bubbles disappear completely 1500-1600m;

c. Brittle ice zone (800-1200m); ice often fractures upon return to surface

d. deep stable ice

2. Bubbles reform upon return of deep ice to surface

3. Exclusion of soluble salts from ice crystals and grain-boundary H_2SO_4



Bulk density and bubble volume versus depth at Siple Station. Each point represents a 1m average.

II. Chronology

A. Annual counting

1. In the upper part of the ice, annual variations in O and H isotopes can be used to count annual layers. As the ice gets older, molecular diffusion blurs the cycles and they become ambiguous, hence limiting O18 cycle counting to the upper portion of the core (~1000 years or so, depending on accumulation rate). At low accumulation rates (e.g. South Pole), annual cycles are not at all useful; at higher accumulation rates (e.g. Dye 3), annual $\delta^{18}O$ cycles can be discerned back as far as 3,000 years.

2. Other indicators can show seasonal cycles:
   a. dust
   b. chemical constituents (major ions)
   c. physical properties, such as electrical conductivity
   d. summer "hoar frost" formation (visually apparent on a light table)
   e. Since these properties do not diffuse (significantly), they can record older layers than can $\delta^{18}O$.

3. Any annual counting method will have some ambiguities that may lead to slight over-and under- counts.

B. Flow models. Based on approximations of the physical equations driving ice flow. These may be decent, but they depend on a good knowledge of boundary conditions and their temporal evolution. These work best when used with chronological spikes deep in the record – the model helps “interpolate” between the chronological spikes.

C. Correlation with other climate records

1. Climate record correlations
2. Gas correlations
    a. CO_2
    b. CH_4
    c. $\delta^{18}O_2$

D. Direct dating methods

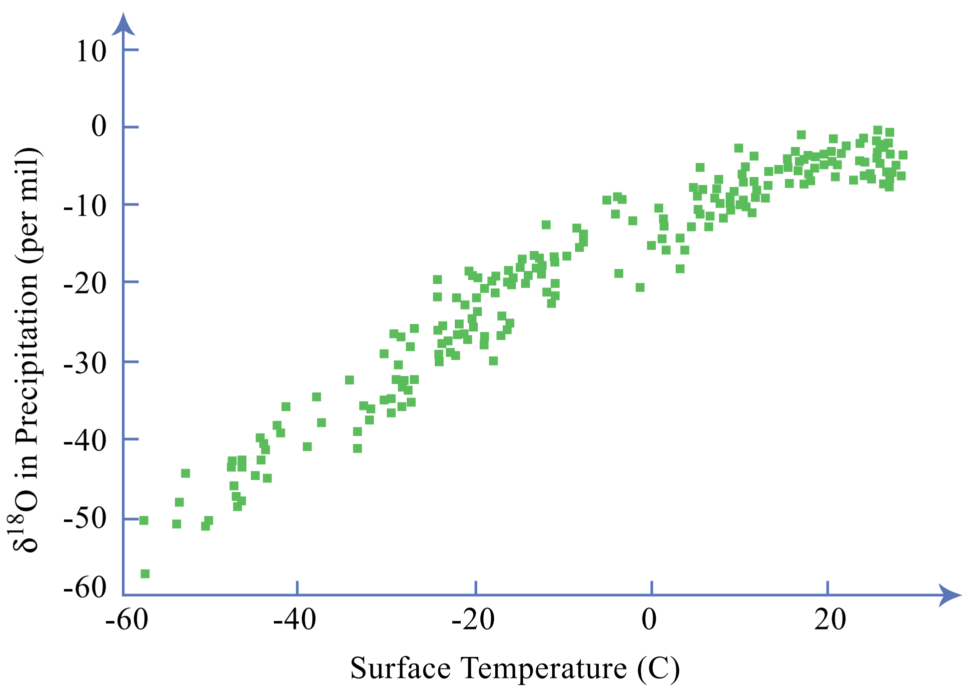
1. In principle, it should be possible to date the CO_2 in the ice bubbles by AMS ^{14}C. In reality, no one has reported a successful ^{14}C date. One problem is that cosmic rays striking the ice convert some of the oxygen to carbon 14 (D. Lal).

E. Other methods

1. Volcanic ash layers
2. Acidity spikes from volcanic eruptions
3. U-series dating of recoil products (Fireman)

III. $\delta^{18}O$ and δD evidence for T changes

A. Stable isotope hydrology



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.

B. "Silty" ice near bottom - problematical $\delta^{18}O$.

C. Camp Century Ice Core

1. Time scale is based on annual cycles of $\delta^{18}O$ for the first millenium.
2. Below that level, time scale is based on flow model and on correlation with other climate records. Note big surprise awaiting on deep Camp Century time scale!
3. Glacial/interglacial climate signal; Younger Dryas; interstadials

Please see:
Figure 6 in Dansgaard W., S. J. Johnsen, H.B. Clausen, and C.C. Langway J. “Climatic record revealed by the Camp Century Ice Core.” In *Late Cenozoic Ice Ages*. Edited by K. K. Turekian. Yale University Press, 1971, pp. 37-56.

Figure removed due to copyright considerations.
Please see:
Figure 9 in Dansgaard W., S. J. Johnsen, H.B. Clausen, and C.C. Langway J. "Climatic record revealed by the Camp Century Ice Core." In *Late Cenozoic Ice Ages*. Edited by K. K. Turekian. Yale University Press, 1971, pp. 37-56.

D. Byrd Ice Core: high resolution Antarctic record

Image removed due to copyright considerations.

E. Dye-3 ice core

1. Confirmation of Younger Dryas, interstadials

2. New time scale assigned to Camp Century core

Image removed due to copyright considerations.
Source: Dansgaard et al. (1982).

F. Vostok ice core

Image removed due to copyright considerations.
Source: Lorius et al. (1985).

Image removed due to copyright considerations.
Source: Jouzel et al. (1987).

Figure removed due to copyright considerations.
Please see:
Figure 3 in Petit, et al. *Nature* 399 (June 3, 1999): 431.

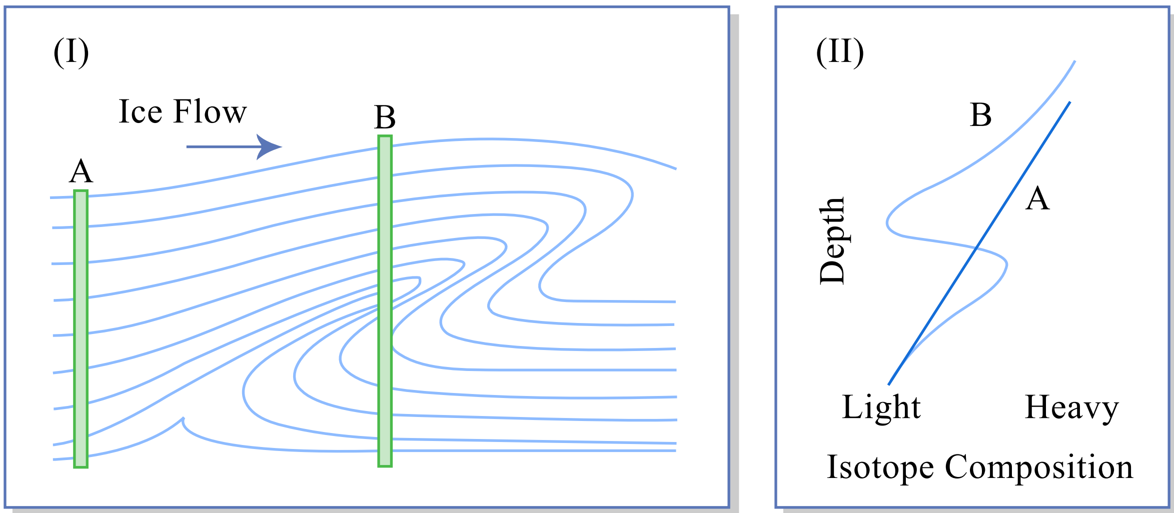
G. Renland ice core (southern Greenland

H. GRIP, GISP2 ice cores in summit, Greenland

Figure removed due to copyright considerations.

Please see:
Grootes P. M., M. Stuiver, J. W. C. White, S. Johnsen, and J. Jouzel. "Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores." *Nature* 366 (1993) 552-554.

GRIP/GISP2 problems: boudinage, basal ice folding



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.

I. Taylor Dome

J. EPICA Dome C

Figure removed due to copyright considerations.
Please see:
The image about EPICA. Dome C. *Nature* 429 (June 10, 2004): 624.

K. North GRIP

Figure removed due to copyright considerations.
Please see:
Figure 2 in *Nature* 431 (September 9, 2004): 148.

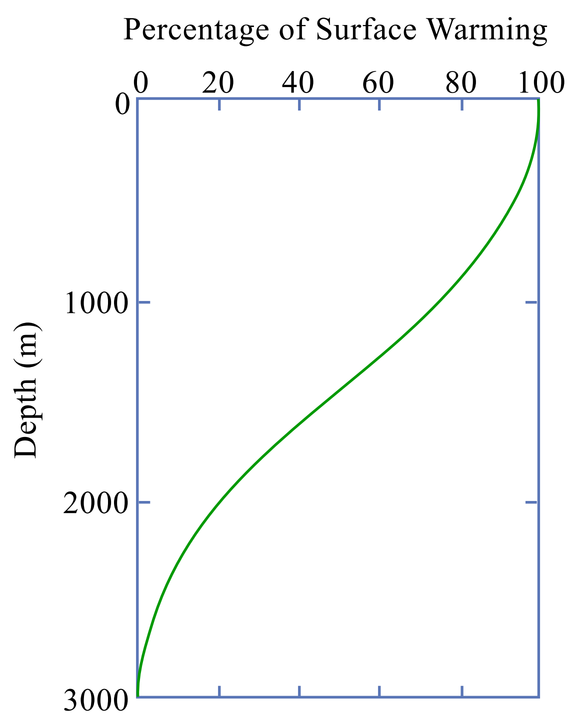
L. Tropical ice cores: Quellcaya (Andes); Tibet

IV. Accumulation Rate

Image removed due to copyright considerations.

V. Are $\delta^{18}O$ and δD accurate temperature recorders?

A. Concept of relic temperatures:



Calculated temperature perturbation in central West Antarctica, 10,000 years after a surface temperature change.

Figure by MIT OpenCourseWare.

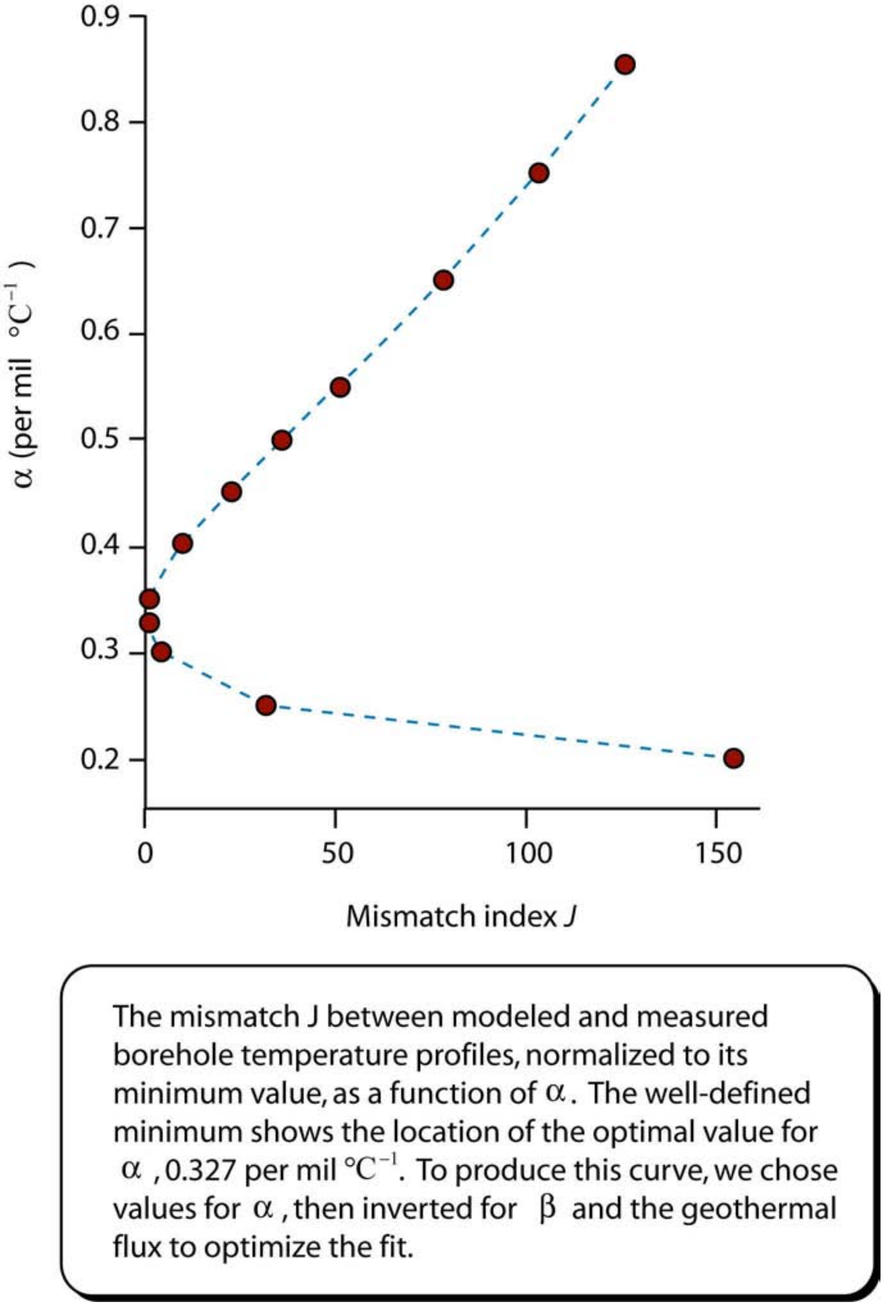
B. Does spatially-calibrated ice core $\delta^{18}O$=temperature?

a. Annual T cycle in central Greenland:

Figure removed due to copyright considerations.
Please see:
Figure 2 in Shuman, C. A., R. B. Alley, et al. "Temperature and accumulation at the Greenland Summit: Comparison of high-resolution isotope profiles and satellite passive microwave brightness temperature trends." J Geophys Res 100 (1995): 9165-9177.

ii. Holocene temperature and isotope variability: The "Little Ice Age" and "Medieval Warm Period" confirmed

b. Borehole temperature analysis of the glacial section of GISP2.



Adapted from source: Cuffey et al. (1995)

b. Monte-Carlo borehole temperature analysis of the glacial section of GRIP.

Image removed due to copyright considerations.

Figure removed due to copyright considerations.
Please see:
Figure 3. “The contour plots of all the GRIP temperature histograms as a function of time.”
Science 282 (October 9, 1998).