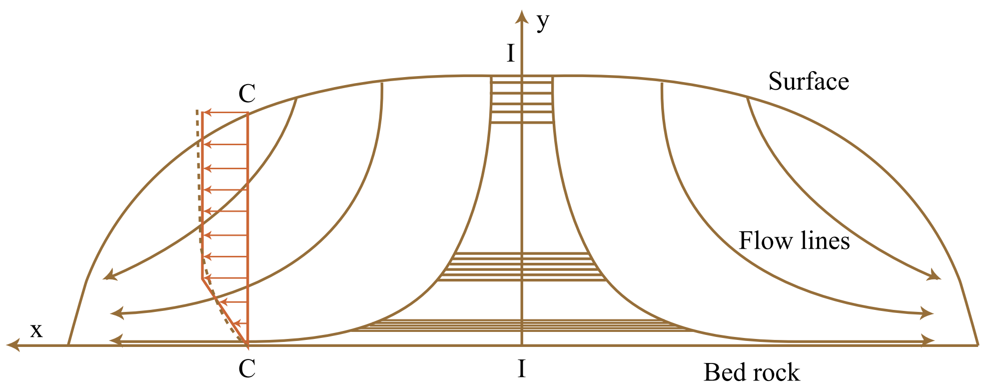
12.740 Paleoceanography
Spring 2008

Ice Core Paleoclimatology I: $\delta^{18}O$, δD, and temperature

12.740 Topic 5 Spring 2008

Because they flow, glaciers are filled from their summits:

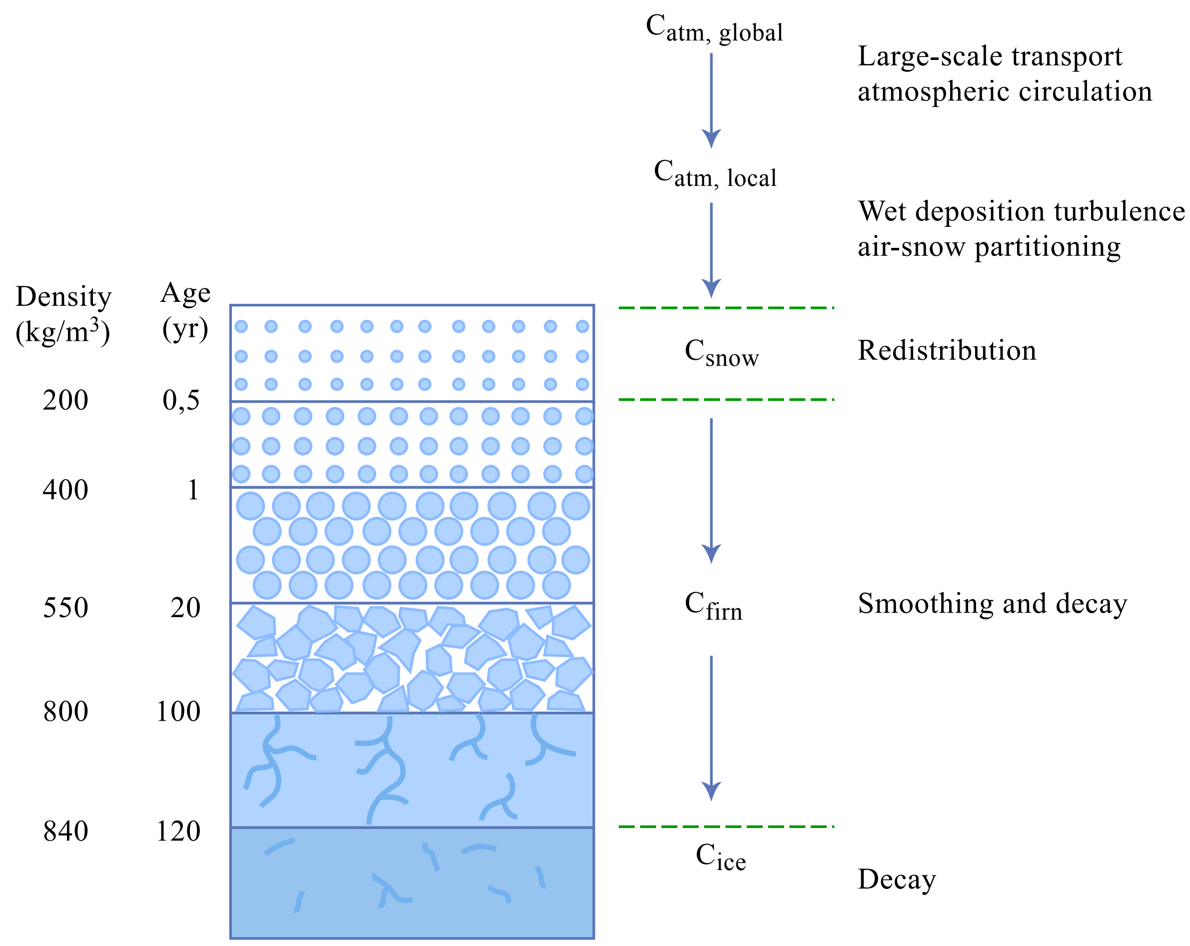
Ice sheets don't represent average snowfall; wastage of the sheet is highest near the southern margin where snowfall is also the highest; glacial flow results in the bulk of the ice sheet representing the isotopic composition of the summits, with more negative $\delta^{18}O$ (-30 to -50 ‰).



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).

Snow -> Firn -> Ice transition



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.

Densification and bubble close-off

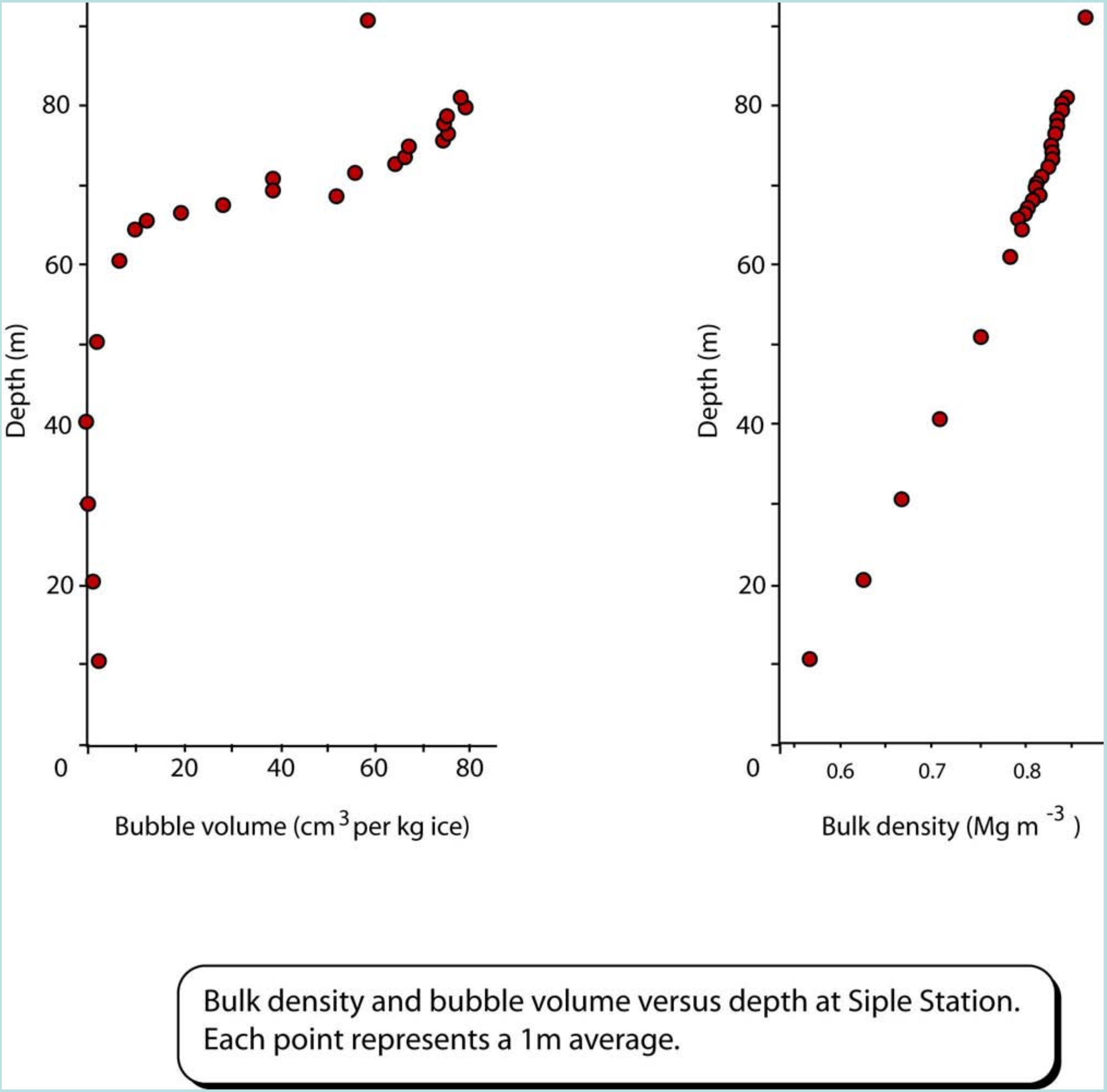


Figure by MIT OpenCourseWare.

Images removed due to copyright restrictions.

M. Battle, M. Bender et al. (1996) Nature 383, 231-235.
Figures 1, 2 and 3.

Ice core chronology

• Annual counting

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.

Other indicators can show seasonal cycles:

dust
chemical constituents (major ions)
physical properties, such as electrical conductivity
summer "hoar frost" formation (visually apparent on a light table)
Since these properties do not diffuse (significantly), they can record older layers than can δ18O.

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

• 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.

• Correlation with other climate records

Climate record correlations
Gas correlations
CO_2
CH_4
$\delta^{18}O_2$

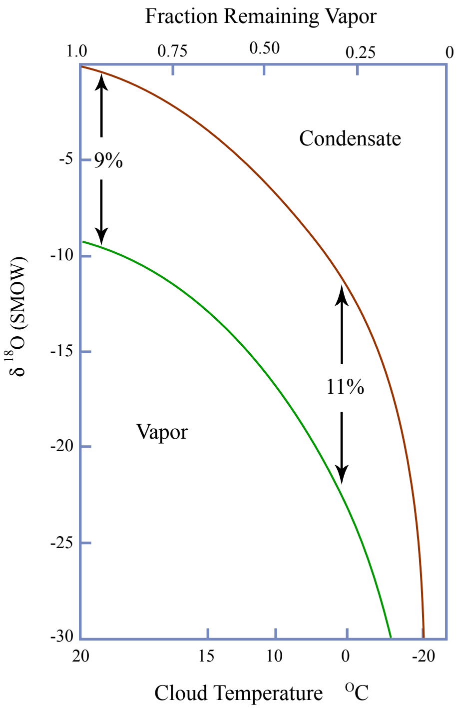
• Direct dating methods

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).

•Other methods

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

Cumulative Rayleigh Isotope Distillation as a function of temperature



$\delta^{18}O$ in cloud vapor and condensate plotted as a function of the remaining vapor in the cloud for a Rayleigh process. The temperature of the cloud in degrees Celsius is shown on the lower axis. $\delta^{18}O$ values are relative to SMOW. The increase in fractionation with decreasing temperature is taken into account. After Dansgaard (1964).

Figure by MIT OpenCourseWare. Adapted from source: Broecker (1974) Chemical Oceanography.

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

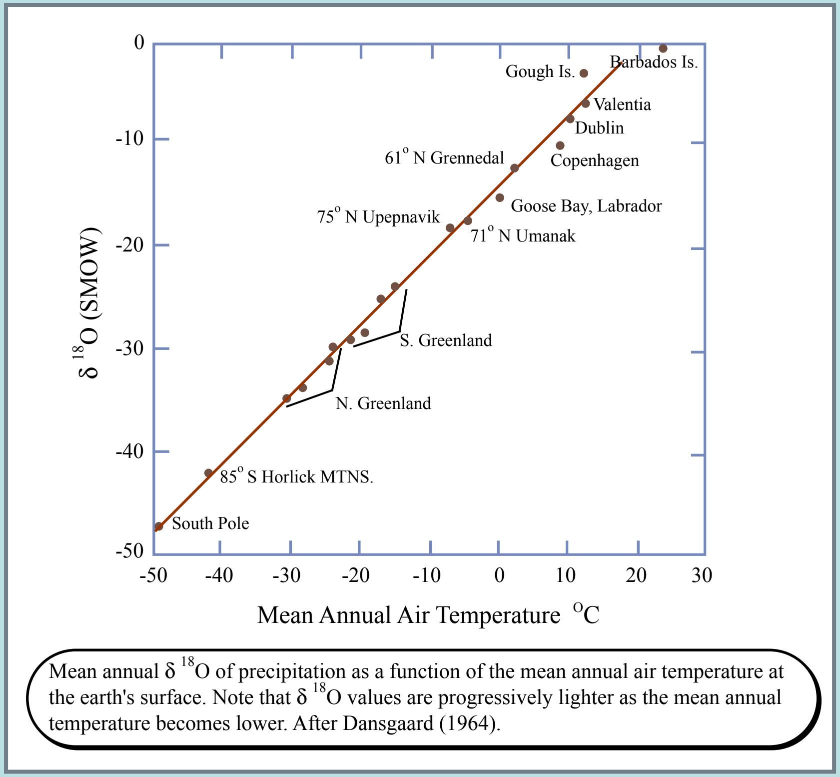
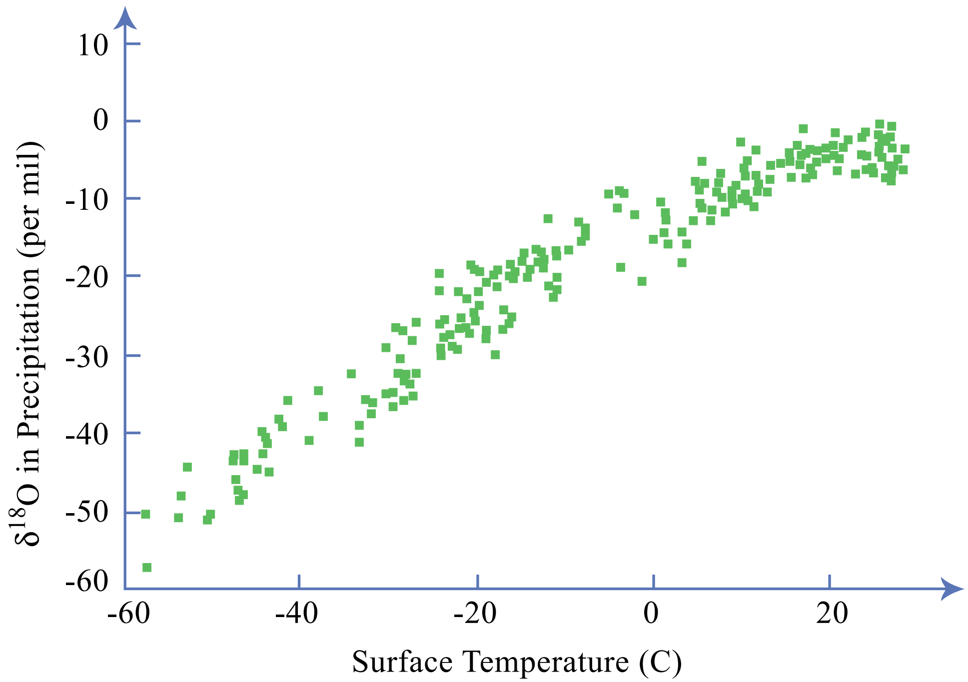


Figure by MIT OpenCourseWare. Adapted from source: Broecker (1974) Chemical Oceanography.

Note: this line is not the relationship predicted by the Rayleigh distillation curve. It includes many other effects: evaporation-precipitation cycles, cloud-T / surface-T relationships; multiple sources of water vapor at different temperatures, etc.

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



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.

Koster et al. modeled $\delta^{18}O$ in annual precipitation

Images removed due to copyright restrictions.

Images removed due to copyright restrictions.

Jouzel et al. modeled vs observed annual precipitation $\delta^{18}O$

Camp Century (NW Greenland) Ice Core

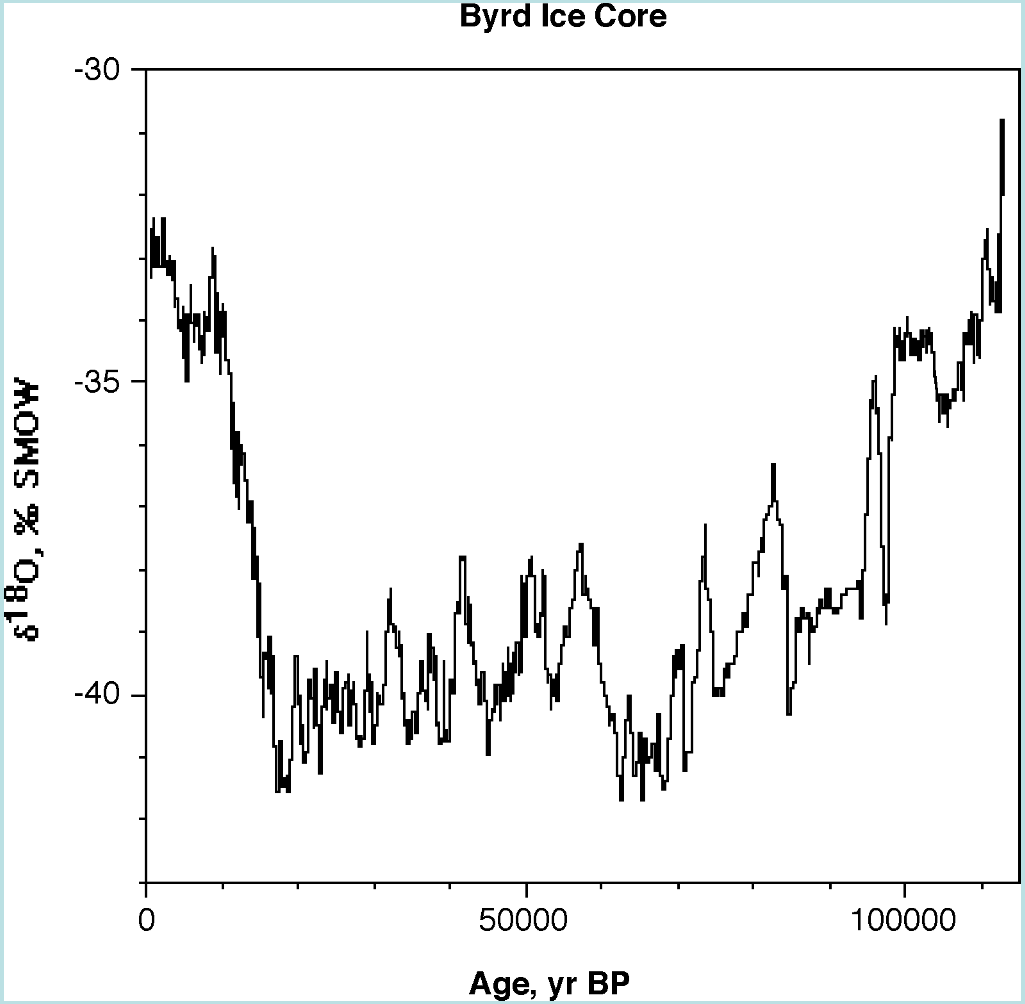
- Most recent time scale is based on annual cycles of $\delta^{18}O$ (the first millenium).

- 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!

- Glacial/interglacial climate signal; Younger Dryas; interstadials

Images removed due to copyright restrictions.

Byrd (West Antarctic) ice core



Dye-3 ice core (southeast Greenland)

- Confirmation (and re-assignment) of Younger Dryas, interstadials
- New time scale assigned to Camp Century core!

Image removed due to copyright restrictions.

source: Dansgaard et al. (1982)

Vostok Ice Core (east central Antarctica)

source: Lorius et al. (1985)

Image removed due to copyright restrictions.

Image removed due to copyright restrictions.

source: Jouzel et al. (1987)

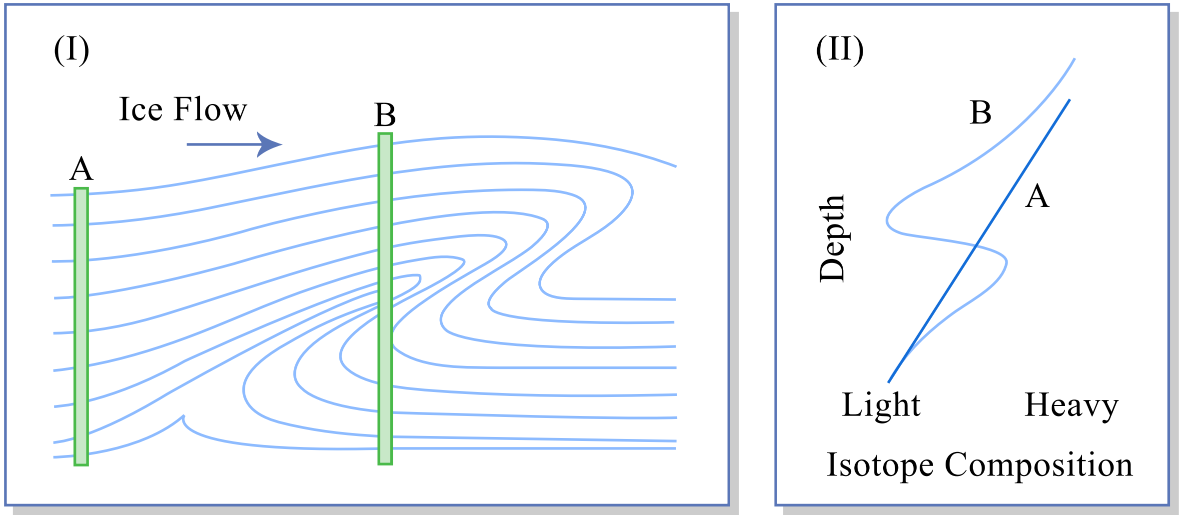
Final version of the Vostok dD record:

Image removed due to copyright restrictions.

source: Petit et al., 1999

Renland Ice Core, southern Greenland

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.

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.

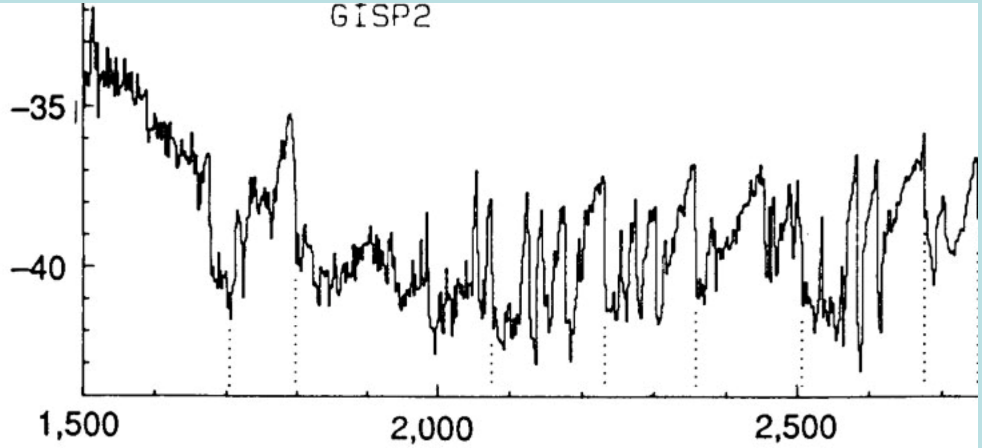


Image removed due to copyright restrictions.

EPICA Dome C δD (top)

compared to

benthic $\delta^{18}O$ (bottom)

Jouzel et al. (2007) Science 317:793

Two ice cores from Antartica

(and two sediment cores)

Image removed due to copyright restrictions.

Nature 429 (10 June 2004): 624. Figure 2.

Dye-3 ice core (southeast Greenland)

- Confirmation (and re-assignment) of Younger Dryas, interstadials
- New time scale assigned to Camp Century core!

Image removed due to copyright restrictions.

source: Dansgaard et al. (1982)

Final version of the Vostok dD record:

Image removed due to copyright restrictions.

source: Petit et al., 1999

Image removed due to copyright restrictions.

EPICA Dome C δD (top)

compared to

benthic $\delta^{18}O$ (bottom)

Jouzel et al. (2007) Science 317:793

Image removed due to copyright restrictions.

GRIP, GISP2 ice cores (central Greenland)

NGRIP

Image removed due to copyright restrictions.

Nature 431 (9 September 2004): 148. Figure 2.

Are $\delta^{18}O$ and δD in ice cores accurate temperature proxies?

GISP2 recent annual cycles $\delta^{18}O$-T correlation

Images removed due to copyright restrictions.

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).

Utah global warming from boreholes

Image removed due to copyright restrictions.

Science 275 (14 March 1997). Figure 1.

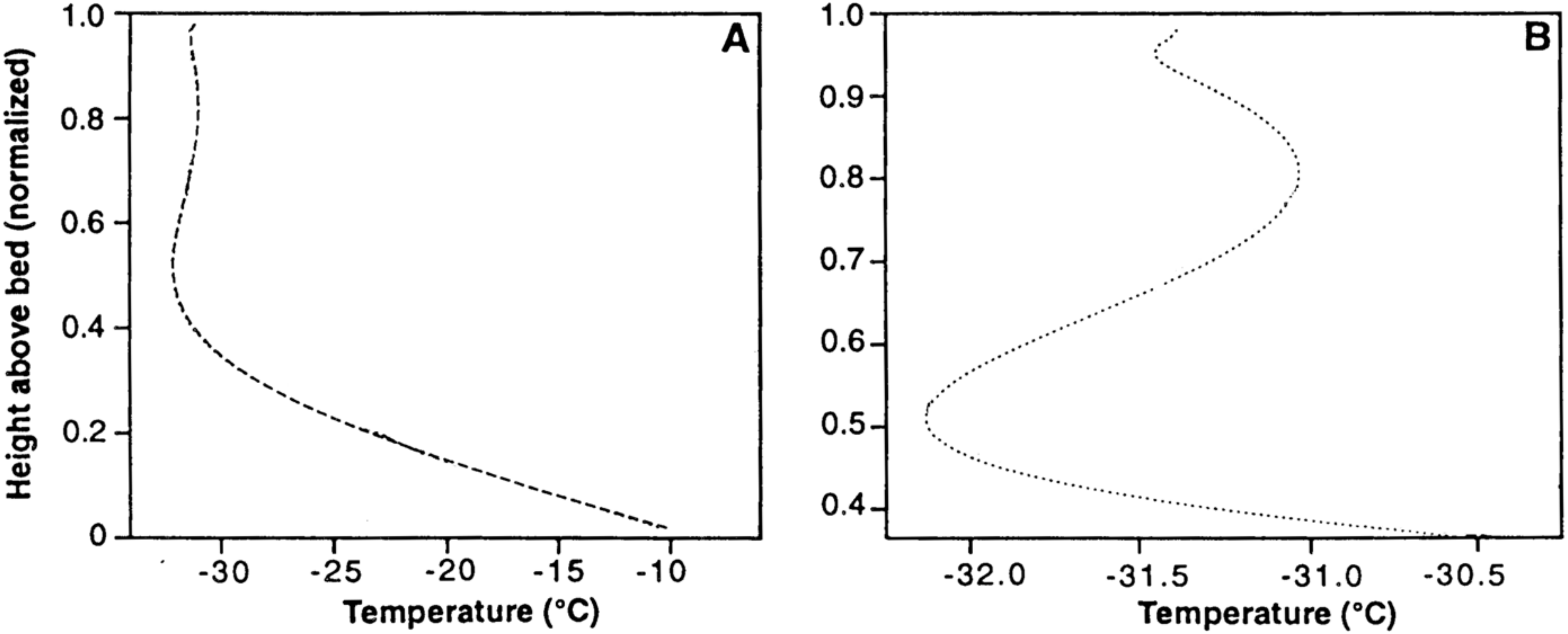
GISP2 last 1400 year borehole T - $\delta^{18}O$ comparison

Images removed due to copyright restrictions.

Images removed due to copyright restrictions.

Cuffey et al. (1994) J. Glaciol. 40

Borehole temperature profiles in central Greenland



Smoothed GISP2 $\delta^{18}O$

Image removed due to copyright restrictions.

Borehole T modeled from $\delta^{18}O$ with changing $\delta^{18}O$-T slopes

Image removed due to copyright restrictions.

Science 270 (20 October 1995). Figures 2 and 3.

GRIP/Dye 3 borehole temperature Monte-Carlo inversions

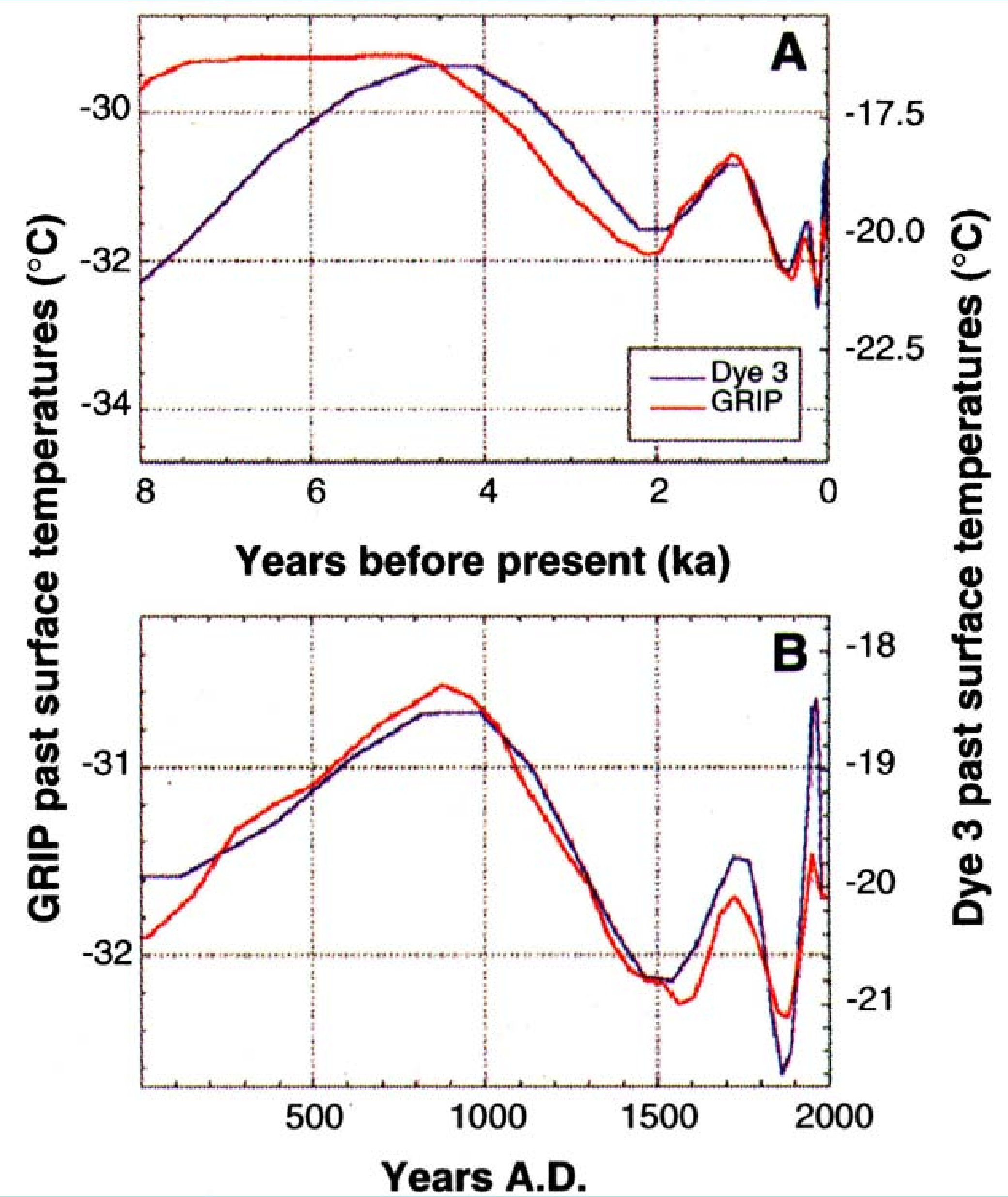


Image removed due to copyright restrictions.

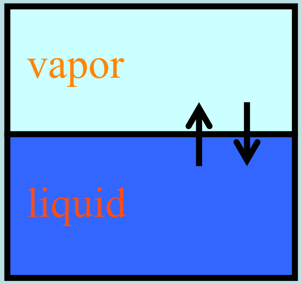
GRIP borehole temperature Monte-Carlo inversions

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.)

Rayleigh distillation of oxygen isotopes



Vapor pressure = f(T)
(Clausius-Clapeyron equation, exponential with increasing T)

At 25°C, the vapor pressure of $H_2{}^{16}O$ is 0.9% higher than $H_2{}^{18}O$

Imagine a 50-50 mixture of liquid $H_2{}^{16}O$ and $H_2{}^{18}O$, equilibrated with the vapor phase at 25°C. Separate the vapor from the liquid:

$\delta^{18}O$ = -9‰
T=25°C

1009 $H_2{}^{16}O$ 1000 $H_2{}^{18}O$

Cool the vapor to 20°C; allow liquid to condense from vapor:

$\delta^{18}O$ = -11‰
T=20°C

745 $H_2{}^{16}O$ 737 $H_2{}^{16}O$

264 $H_2{}^{16}O$ 263 $H_2{}^{18}O$

Alternatively, imagine a 50-50 mixture of liquid $H_2{}^{16}O$ and $H_2{}^{18}O$, equilibrated with the vapor phase at 20°C. Separate the vapor from the liquid:

$\delta^{18}O$ = -9‰
T=20°C

1009 $H_2{}^{16}O$ 1000 $H_2{}^{18}O$

Rayleigh equation: $$\frac{R}{R_0} = f^{\alpha-1}$$

R_0 = initial isotope ratio
R = isotope ratio after cooling
f = fraction of water condensed
α = isotope fractionation factor

Image removed due to copyright restrictions.

Family of Rayleigh distillation curves

Boyle (1999)
Geophys. Res. Lett.
24:273-276

Shift in *intercept* of LGM $\delta^{18}O$-T relationship due to cool tropical/subtropical temperatures?

Image removed due to copyright restrictions.

Boyle (1999)
Geophys. Res. Lett.
24:273-276

Alternative:

Suppose it just didn't snow in central Greenland during the LGM winter (too cold, too dry, wrong storm track pathways…). Then $\delta^{18}O$ of the ice would only reflect summer T, not the mean annual T (M. Werner et al.,2000, Geophys. Res. Lett. 27:723)

Best guess as of now: the source vapor temperature matters somewhat, but the discrepancy is dominated by low winter snowfall. So LGM annual temperatures in Greenland were ~ a factor of two lower than "modern spatial calibration $\delta^{18}O$" indicates. It is argued that Antarctic cores don't show this effect.

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.

Petit et al (1999) in Kump (2002) *Nature*, 419:188-190.

Image removed due to copyright restrictions.

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

Reading (1)

* Barnola, J.M., Raynaud, D., Korotkevitch, Y.S. and Lorius, C., 1987. Vostok ice core: a 160,000-year record of atmospheric CO2. Nature, 329:408-414.

* Bender, M., T. Sowers, M.-L. Dickson, J. Orchardo, P. Grootes, P. Mayewski, and D.A. Meese, Climate correlations between Greenland and Antarctica during the past 100,000 years, Nature, 372, 663-666, 1994a.

Bender, M., T. Sowers, and L. Labeyrie, The Dole effect and its variations during the last 130,000 years as measured in the Vostok ice core, Glob. Biogeochem. Cyc., 8, 363-376, 1994b.

Blunier, T. and E. Brook (2001) Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, Science 291:109-112

Boyle, E.A. (1997) Cool tropical temperatures shift the global d18O-T relationship: an explanation for the Ice Core δ18O / borehole thermometry conflict?, Geophys. Res. Lett. 24:273-276.

Craig H., Horibe Y. ,and Sowers T. (1988) Gravitational separation of gases and isotopes in polar ice caps. Science. 242, 1675-1678.

Cuffey, K.M., G.D. Clow, R.B. Alley, M. Stuiver, E.D. Waddington, and R.W. Saltus, Large Arctic Temperature Change at the Wisconsin-Holocene Glacial Transition, Science, 270, 455-458, 1995.

Dahl-Jensen, D., K. Mosegaard, et al. (1998). "Past temperatures directly from the Greenland ice sheet." Science 282: 268-271.

Dansgaard W., Johnsen S. J., Clausen H. B. ,and C.C. Langway J. (1971) Climatic record revealed by the Camp Century Ice Core. In Late Cenozoic Ice Ages (ed. K. K. Turekian), Vol. pp. 37-56. Yale University Press.

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

Hammer, C.U., Clausen, H.B. and Tauber, H., 1986. Ice-core dating of the Pleistocene/Holocene boundary applied to a calibration of the 14C time scale, Radiocarbon. 28, 284-291:.

Hammer C. U., Clausen H. B., Dansgaard W., Neftel A., Kristinsdottir P. ,and Johnson E. (1985) Continuous impurity analysis along the Dye 3 deep core. In Greenland Ice Core: Geophysics, Geochemistry, and the Environment (ed. C. C. LangwayJr., H. Oeschger and W. Dansgaard), Vol. 33, pp. 90-94. Am. Geophys. Union.

Herron M. M. , and Langway Jr. C. C. (1985) Chloride, nitrate, and sulfate in the Dye 3 and Camp Century, Greenland ice cores. In Greenland Ice Core: Geophysics, Geochemistry, and the Environment (ed. C. C. LangwayJr., H. Oeschger and W. Dansgaard), Vol. 33, pp. 77-84. Am. Geophys. Union.*Jouzel, J., Raisbeck, G., Benoist, J.P., Yiou, F., Lorius, C., Raynaud, D. and J.R. Petit, N.I. Barkov, Y.S. Kortkevitch, and V.M. Kotlyakov, 1989. A comparison of deep Antarctic ice cores and their implications for climate between 65,000 and 15,000 years ago. Quat. Res., 31:135-150.

Indermühle A., Stocker T. F., Joos F., Fischer H., Smith H. J., Wahlen M., Deck B., Mastroianni D., Tschumi J., Blunier T., Meyer R., and Stauffer B. (1999) Holocene carbon-cycle dynamics based on CO2 trapped in ice at Taylor Dome, Antarctica. Nature 398, 121-126.

* Jouzel J., Lorius C., Petit J. R., Genthon C., Barkov N. I., Kotlyakov V. M. ,and Petrov V. M. (1987) Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). Nature. 329, 403-408.

* Jouzel J., Barkov N. I., Barnola J. M., Bender M., Chappellaz J., Genthon C., Kotlyakov V. M., Lipenkov V., Lorius C., Petit J. R., Raynaud D., Raisbeck G., Ritz C., Sowers T., Stievenard M., Yiou F. ,and Yiou P. (1993) Extending the Vostok ice-core record of paleoclimate to the penultimate glacial period. Nature. 364, 407-412.

Landais, A., J. Jouzel, V. Masson-Delmotte, N. Caillona (2005) Large temperature variations over rapid climatic events in Greenland: a method based on air isotopic measurements, C.R. Geoscience 337:947–956.

Legrand M., Feniet-Saigne C., Saltzman E. S., Germain C., Barkov N. I. ,and Petrov V. N. (1991) Ice-core record of oceanic emissions of dimethylsulphide during the last climate cycle. Nature. 350, 144-146.

Reading (2)

Mayewski, P.A., L.D. Meeker, M.S. Twickler, S.I. Whitlow, Q. Yang, W.B. Lyons, and M. Prentice (1997) Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series, J. Geophys. Res. 102:26345-26366.

Mulvaney R., Wolff E. W. ,and Oates K. (1988) Sulfuric acid at grain boundaries in Antarctic ice. Nature. 331, 247-249.

* Neftel, A., Oeschger, H., Staffelbach, T. and Stauffer, B., 1988. CO2 record in the Byrd ice core 50,000-5,000 years BP. Nature, 331:609-611.

Neftel, A., Moor, E., Oeschger, H. and Stauffer, B., 1985. Evidence from polar ice cores for the increase in atmospheric CO2 in the past two centuries. Nature, 315:45-47.

Schwander J. ,and Stauffer B. (1984) Age difference between polar ice and the air trapped in its bubbles. Nature. 311, 45-47.

Severinghaus J. P., Sowers T., Brook E. J., Alley R. B., and Bender M. L. (1998) Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice. Nature 391, 141-146.

Shoji H. ,and Langway Jr. C. C. (1985) Mechanical properties of fresh ice core from Dye 3, Greenland. In Greenland Ice Core: Geophysics, Geochemistry, and the Environment (ed. C. C. LangwayJr., H. Oeschger and W. Dansgaard), Vol. 33, pp. 39-48. Am. Geophys. Union.

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

Ram M. ,and Gayley R. I. (1991) Long-range transport of volcanic ash to the Greenland ice sheet. Nature. 349, 401-404.

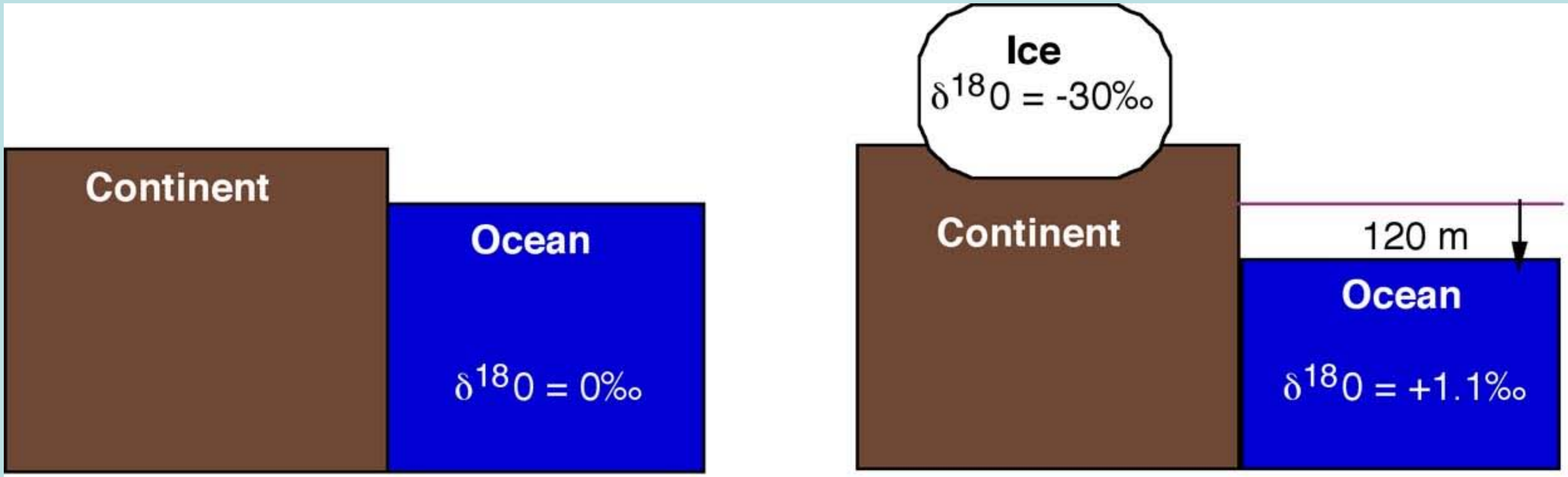
* Sowers, T., Bender M., Labeyrie L., Martinson D., Jouzel J., Raynaud D., Pichon J. J. ,and Korotkevich Y. S. (1993) A 135,000-year Vostok-Specmap common temporal framework. Paleoceanogr. 8, 699-736.

* Sowers, T., and M. Bender, Climate records covering the last deglaciation, Science, 269, 210-214, 1995.

Zielinksi G. A., Mayewski P. A., Meeker L. D., Whitlow W., and Twickler M. S. (1996) Potential atmospheric impact of the Toba mega-eruption ~71,000 years ago. Geophys. Res. Lett. 23, 837-840.

Also note: a volume of joint GISP2/GRIP results were published in JGR vol. 102 (1997, #C12 pp. 26315-26886). Many worthwhile results and summaries are contained within.

Effect of glaciation on the oxygen isotope composition of the ocean



Modern Ocean

Last Glacial Maximum
(18,000 years Before Present)

Isotope Mass Balance Equation:

$$M_o\delta_o + M_i\delta_i = M_t\delta_t$$

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

Image removed due to copyright restrictions.