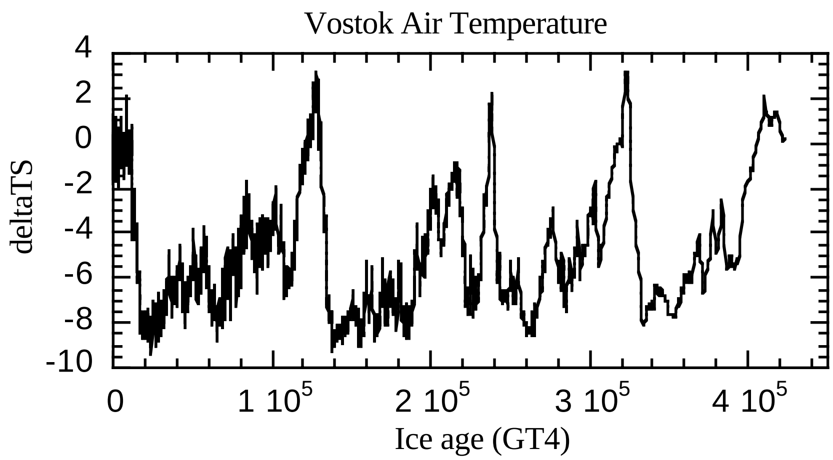
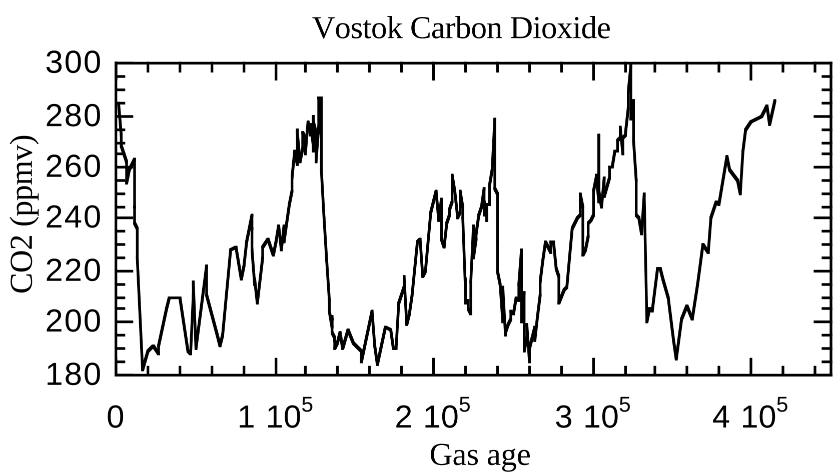
Ice Core Data:

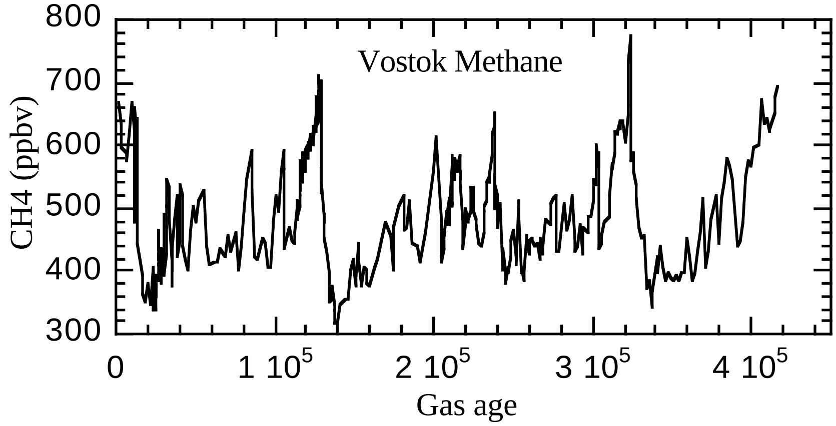
Antarctica and Greenland both have coverings of about 3000 meters of ice, which have been laid down over a period of 200-500Kyr. This time history can be used to estimate time histories of a number of things. Near the surface in regions of high accumulation, annual and even seasonal information can be determined for 100s of years. In regions of slower accumulation rate, longer histories with less time resolution can be determined. Because ice flows, at depth the ice can be folded and sheared, causing problems with assuming that depth is monotonically related to time. For this reason the deepest, oldest cores are drilled near the summit of the ice sheet, where flow may be less of a problem.

Stable Oxygen and Hydrogen Isotopes in Ice.

Precipitation is an isotopic fractionation process because heavier isotopes tend to condense first. The water vapor remaining in a given air mass is thus depleted in the heavier isotopes as it cools and condenses. Therefore δD (deuterium anomaly) and $\delta^{18}O$ in the water in ice cores tend to vary linearly with the temperature at which the ice condenses. This can be verified with modern data by observing the isotopic abundances of surface ice as a function of latitude and altitude of the ice cap, which are related to temperature. Because the isotopic abundance is a measure of the isotopic depletion by condensation, the isotopic abundances also depend on the time history of the air mass. Differences between temperature inferences from δD and $\delta^{18}O$ can be used to guess something about circulation.

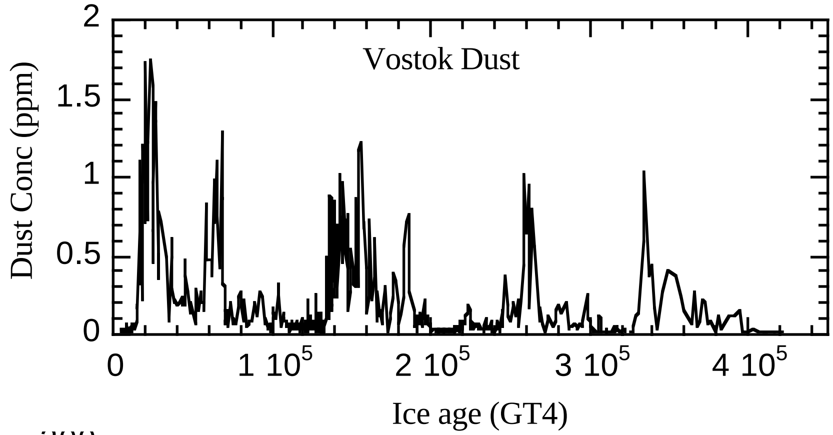


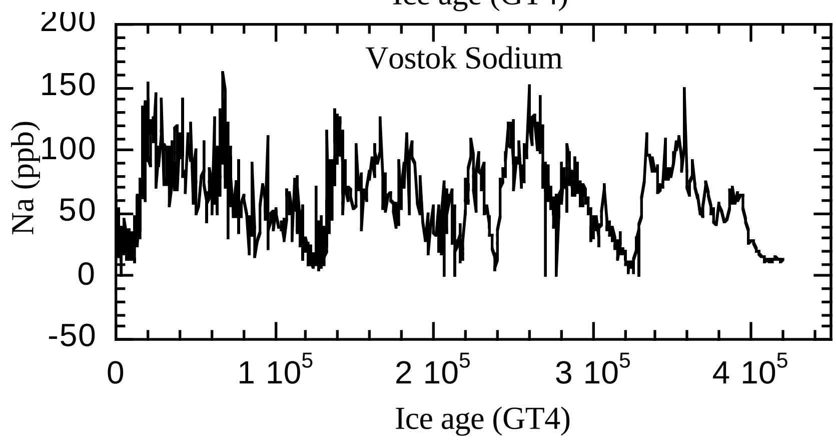




Dust and Gases in Ice Cores.

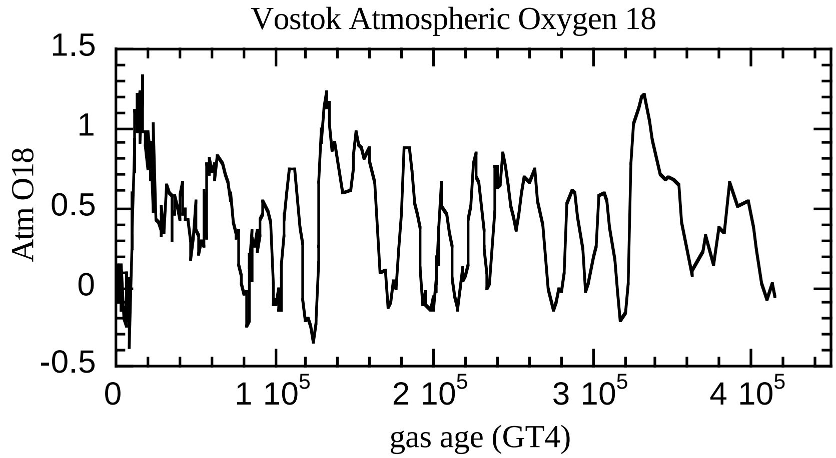
You can also get dust loading, chemical information, and gas concentrations trapped in bubbles, which can be assumed to be those of the air at some time after the ice was formed. Because the gases communicate with the atmosphere down to a depth of many meters, the gases are generally younger than the ice in which they are embedded. This is adjusted for by modeling. The data shown here are taken from the work of Petit, et al.(1999)





$\delta^{18}O$ in the bubbles of gas in ice cores:

The bubbles in ice cores are a measure of the $\delta^{18}O_{atm}$ in the atmosphere, which are related to the $\delta^{18}O_{sw}$ in the seawater. The ocean water and atmosphere $\delta^{18}O$ are different, but this difference, the Dole effect, seems to be constant with time.



Petit et al.(1999) summarize the information from the 420Kyr record in the Vostok core. Vostok is a Russian station on the central East Antarctic dome at 78˚28'S 106˚48'E, elevation 3490m.

1.) Temperatures over the ice sheets have varied between relatively fixed highs and lows over the last 420Kyrs. with strong 100Kyr and 41Kyr rhythms. The temperature range is about 8K at the inversion and 12K at the surface.

2.) $\delta^{18}O_{atm}$, which is thought to be related closely to global ice volume, is closely related to variations in insolation at 65N, more or less in agreement with the Milankovitch orbital parameter theory.

3.) More aerosols are present during the ice ages. Sea salt is up a factor of 3-4 and dust is up a factor of 20 or more. The evidence of dustier times during ice ages is consistent with loess deposits and other geological evidence. Sea salt is up despite the greater extent of sea ice around Antarctica during a glacial advance. This must be because greater storminess and lower atmospheric humidity offset the greater distance from Antarctica to open ocean during a glacial advance.

4.) Concentrations of both CO_2 and CH_4 are remarkably proportional to temperature estimated from δD and $\delta^{18}O$ in ice. The magnitudes of the changes in concentration, especially of CO_2, are climatically relevant. You can account for about half of the cooling during an ice age with forcing by greenhouse gas changes and associated water vapor feedback. As we shall see later, the CO_2 variations constitute a strong positive feedback. Temporal variations in CH_4 are somewhat different, since they are believed to arise mostly from variations in wetland production of CH_4, whereas CO_2 depends on ocean biochemistry and forest chemistry/biology. Ice cores also show that CH_4 was about 700ppbv for most of the Holocene and has grown up to its present value of about 1600 in the last couple of centuries (Blunier, et al. 1995).

5.) Terminations of glacial periods are rather abrupt and occur about every 100Kyr. These times can be used to gauge the cause and effect relationship between ice volume growth, greenhouse gases, temperature and dust loading. Broecker and Henderson(1998) looked carefully at events surrounding Termination II, the end of the penultimate glacial maximum about 140,000 years ago. The data suggest that temperature and CO_2 content rise together over an 8,000-year period. At the beginning of this period the dust content drops and at the end of this period the $\delta^{18}O$ in the air in ice core bubbles drops. Dust begins to increase rapidly when Vostok temperature drops by more than 4˚C below modern values. This is taken to indicate dry, dusty conditions over the continents, probably mostly from Patagonia. Based on comparisons with ocean cores, they suggest that the $\delta^{18}O_{atm}$ in ice core air is a proxy for global ice volume rather than temperature. They conclude that the CO_2 and temperature rise precede the ice sheet demise. Since the dust flux drops off prior to the warming, they hypothesize that the dust flux cutoff, importantly soluble iron, is the trigger that sets off the CO_2-driven warming. Trace minerals from land are critical for primary production in the ocean and may be a key constraint on the biological pump of carbon(Martin 1990, Martin, et al. 1990, Martin 1994). They also implicate the southern ocean as the key region for governing atmospheric CO2 on glacial time scales. In the Antarctic, both sunlight and deposition of trace metals may limit primary productivity by airborne dust. A feedback between orbital parameter changes of insolation causing ice ages and higher and drier winds providing dust to the oceans could be important. The effect of ice on sea level does not seem to be important for the greenhouse gas concentrations or warming, because these change before global ice volume responds. These conclusions are supported by analysis of terminations III and IV by Petit et al.(1999). The lag between warming and deglaciation for terminations II and IV (9Kyrs) is greater than that for terminations I and III(4-5 Kyrs). The uncertainty is about 1Kyr.

High-Frequency Fluctuations:

Data from Greenland ice cores give better time resolution because of the higher accumulation rate of the ice sheet there. Several long cores have been obtained from near the summit of the Greenland ice sheet in recent years(1992) by both American and European teams.

The European team collected a 3,000-meter core from near the summit of the Greenland Ice sheet (72.58N, 37.64W) where its top is 3,238m above sea level. The $\delta^{18}O$ record from this core is shown in Dansgaard, et al.(1993). About half of the core (1,500 meters) accounts for the last 10,000 years, during which period there was very little variation in $\delta^{18}O_{sw}$. The bottom 1,500 meters takes us back to about 250Kya. Of interest in this core are the apparently rapid fluctuations during the last interglacial about 125,000 years ago, contrasted with the stable climate of the last 10Kyr. While we knew that big fluctuations took place during the glacial periods and during their decline, we had not seen evidence of big variations within the interglacials before. A comparison of the Summit(GRIP) ice core data with some other data suggests that he Eemian interglacial lasts longer in the GRIP core than in other data. Maybe this is because of the instability at the end of it in the North Atlantic.

Consider a couple of events discussed by Anklin et al.(1993). One event at the culmination of the Eemian interglacial about 115Kya was a cooling event that lasted about 70 years, and took the climate from full interglacial to mid-glacial(about like the Younger Dryas event) in a period of a decade or less. This is a very rapid change. These rapid changes into cool events are sometimes called Dansgaard-Oeschger events, especially by Broecker.

Another event in the initial stages of the Eemian event about 115Kya lasted about 750 years. These rapid, but long lasting changes suggest the involvement of changes in the ocean-atmosphere circulation.

More recent analysis comparing the GRIP and GISP2 cores for both conductivity and oxygen isotope continuity show that the two cores agreed very well up to about 2700 meters, but that for the last 10% of the core there is little agreement between the features seen. This brings their interpretation into question, since they are only 28 km apart and the idea of drilling them both was for a validity check. The time when the coherence between the two cores appears is at about 100Kbp, so all the stuff about breaks and instability in the Eemian interglacial is basically unvalidated.

Ocean cores from the North Atlantic also agree with the two ice cores until about 100Kbp, and then diverge. The ocean cores show a more stable, slowly changing climate. McManus, et al.(1994). McManus, et al.(1999) argue on the basis of ocean cores from the Atlantic that whenever the ice volume surpasses an amount corresponding to a $\delta^{18}O_{sw}$ anomaly of 3.5 per mil, the North Atlantic climate becomes metastable and exhibits rapid fluctuations of order 4 to 6 C, compared to 1-2C fluctuations when the ice volume is less than this threshold. These events are related to the millennial scale Heinrich events that are marked by enhanced glacial discharge of icebergs (Heinrich 1988, Bond, et al. 1992).

A recent analysis of Greenland and Antarctic cores has been conducted to see if the rapid Dansgaard-Oeschger events in the Greenland $\delta^{18}O$ ice cores have a corresponding signal in CO_2(Stauffer, et al. 1998). The high dust content of the Greenland cores can cause artifacts in the CO_2. It appears that some of the CO_2 maxima inferred in Greenland cores during warm D-O events are caused by acid decomposition of carbonates or decay of organic matter trapped in the core(Tschumi and Stauffer 2000). Stauffer et al.(1998) looked in the Antarctic cores for the D-O event CO_2 signal, since the Antarctic cores are cleaner, with less dust, crud, and acid included. To do this they used the methane signals to develop a common time scale for the two cores. Methane is thought to be determined in warm wetlands, and has a fast mixing time in the atmosphere relative to its chemical relaxation time, so that the signals in methane should be contemporaneous in both polar regions. They found that the shorter D-O events had a very small CO_2 signal (< 10 ppmv), but that the longer D-O events bounded by Heinrich events were associated with a significant CO_2 signal of order 20 ppmv. Thus the short D-O events are a local cooling in the North Atlantic that occur independent of CO_2 , but the Heinrich events result in a net change of ocean productivity. If the Heinrich events are associated with a thin stable layer over the North Atlantic, then this could result in a loss of productivity of the North Atlantic.

Blunier, et al.(1998) use methane in ice cores to line up Arctic and Antarctic cores. They find that the Antarctic LEADS the Arctic by 1.0 to 2.5 Kyr during the period 47-23Kyr before present. This is a very odd result for those who think that North Atlantic deep water formation is the trigger for these rapid climate fluctuations.

Raymo et al.(1998) show that the high-frequency fluctuations in North Atlantic climate occurred over one million years ago, when the climate was a little warmer and the cycles were 40,000 years instead of 100,000 years. So these short period fluctuations are not dependent on the exact conditions that we have to day, but are a more general phenomenon.

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