3 Ice Cores and Palaeoclimate

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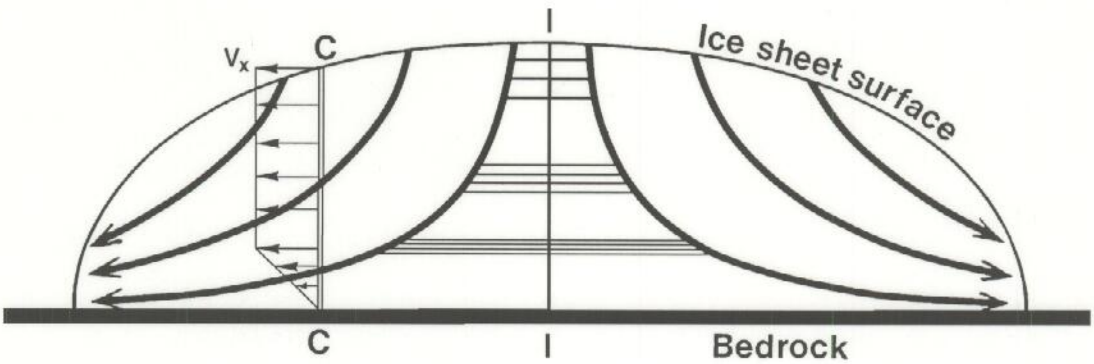
1. Introduction

Ice sheets and glaciers form in areas where the annual snowfall exceeds the annual melt-off over a long period of time. Today glaciers are found worldwide; but large ice sheets are only found in the polar regions. Both glaciers and ice sheets build up from snowfall and may thus be regarded as atmospheric sediment. This sediment contains mainly the snow itself, but also samples of the past atmosphere are trapped in bubbles in the ice. Along with the snow a wide range of different substances from the atmospheric aerosol are deposited in the glacier.

As layer upon layer of consecutive snow falls are deposited in the glaciers accumulation area the snow is buried and gradually transformed into ice due to the increasing weight of the overburden snow. The ice layers are then further compressed by depth, and they get thinner as they start to spread due to increasing pressure. This is visualised in Figure 1. The glacier ice flows from the accumulation area down into the ablation area where it is eventually lost as melt off or calving icebergs, i. e. ablation. If the total accumulation of a glacier or an ice sheet is the same as the total loss, the glacier is said to be in mass balance. The two largest ice sheets in the world, the Antarctic and the Greenland ice sheets, are close to being in mass balance, but it is very difficult to assess the total accumulation and ablation of a large ice sheet with a sufficient accuracy to exactly quantify a current waxing or waning.

Figure 1 Illustration of the ice flow in an ice cap including the size of the horisontal flow velocity.



Ice cores drilled in glaciers contain progressively older layers of ice. If the drill site is chosen carefully the layers of old snowfalls will mainly have moved downwards since deposition on the surface. The layers get thinner with depth; but they are not mixed, which is why ice cores constitute a very reliable stratigraphical record of past atmospheric precipitation.

Among the first scientists to realise the potential of ice core studies in palaeoclimatic reseach was Prof. W. Dansgaard from the University of Copenhagen who had discovered the connection between the stable isotopic ratio ($^{18}O/^{16}O$) of precipitation and cloud temperature[1]. Prof. C. Langway of U.S. Army C.R.E.E.L. found the first stratified records in ice cores. In the late 60's the two joined forces, and established a very fruitful collaboration.

In the early 70's the first publications on stratigraphic records from deep ice cores appeared: The Camp Century record from Northwest Greenland and the Byrd record from Antarctica. The results from these cores revealed several surprises. Both records showed that ice from the last ice age had a very different stable isotopic ratio than ice from the present warmer climate. Furthermore, the Camp Century record showed that the last ice age in Greenland terminated rapidly, and that the last ice age was climatically unstable with many sudden climate changes. The Byrd glacial record however did not show such rapid changes, and the validity of the Camp Century ice age record was questioned.

The success of the Byrd and Camp Century studies was continued in the Greenland Ice Sheet Project (GISP). The main goal of GISP was to obtain a Greenland deep ice core in collaboration between the U.S. National Science Foundation, the University of Copenhagen and the University of Bern, Switzerland. GISP succeeded in obtaining a deep ice core from Dye-3 in South Greenland in 1981.

The record from the Dye-3 ice core confirmed the Camp Century record. It contained the termination of the last ice age and the sudden climatic changes during the last ice age in much greater detail. This meant that Greenland ice core records did reveal climate changes that were representative for at least the whole Greenland region. At the same time other ice cores from Antarctica confirmed the Byrd ice core record. It became clear, that Greenland and Antarctica had experienced two different histories: In Greenland the ice age terminated abruptly and during the ice age more than 20 sudden climatic changes were detected. In Antarctica, the termination of the last ice age was more gradual, and sudden changes during the ice age were less pronounced (see Figure 5).

The temporal resolution of the Dye-3 record was high enough to allow for a detailed study of the termination of the last ice age. The isotopic record showed that the average temperature in Greenland had changed significantly (about 10 °C) within 40 years. The concentration of aeolian continental dust had even changed by a factor of 50 in less than 20 years. With these findings the concept of fast and sudden climate changes as well as climatic instability had clearly been manifested.

During the 80's and 90's, studies of ocean sediment cores and terrestrial sediment records have revealed that the fast climatic variations seen in the last glacial part of Greenland ice cores are also found in North America, Northern Europe and the North Atlantic. Even some Chinese loess records show abrupt climate changes during the last glacial. The ice core records of Greenland thus reflect climatic changes that affected at least the North Atlantic, and possibly the whole Northern Hemisphere.

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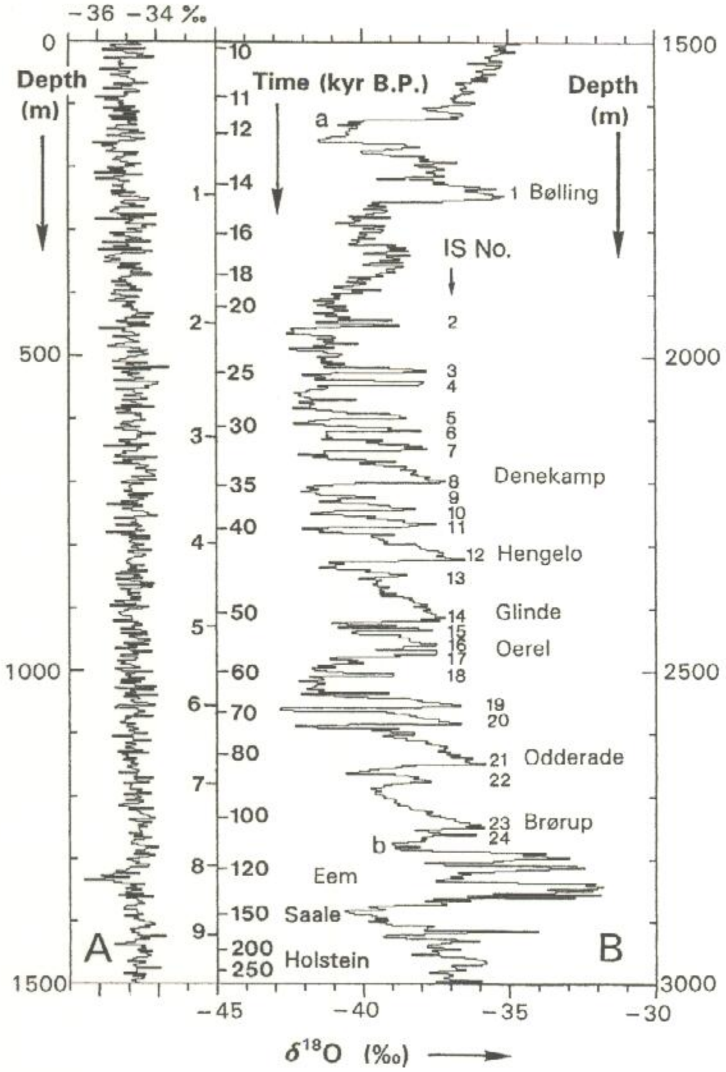
[1] The deviation of the ratio *R* between the concentration of ^{18}O and ^{16}O from a "Standard Mean Ocean Water" sample is given by $\delta^{18}O=(R-R_{SMOW})/R_{SMOW} * 10^3$ per mill.

Figure 2 The $\delta^{18}O$ curve from the GRIP ice core. The outer axis on both plots show the linearly increasing depth of the core, whereas the inner axis displays the increasing age. The left hand side of the plot, A, depicts the upper 1500 m's, closely corresponding to the present warm period, the Holocene. The right hand side, B, shows the lower 1500 m of the core, including the last ice age, and the previous warm period, the Eemian. During the last glacial period 24 distinctive inter-stadials are annotated, in some cases in combination with their geological names. The very cold period ~ 23,000 yrs BP is commonly referred to as the Last Glacial Maximum (LGM). Figure from Dansgaard et al., 1993.



In the early 90's two deep ice cores were drilled to bedrock at the Summit of the Greenland ice sheet: The U.S. GISP2 ice core and the European GRIP ice core. Both ice cores were more than 3 km long, and they confirmed earlier findings, with even higher temporal resolution. Dust measurements on the GISP2 core revealed that in terms of atmospheric circulation the ice age ended in less than 5 years. New experimental techniques were employed allowing for detailed studies of isotopes, chemical composition of the ice, dust, radionucleides and greenhouse gases in bubbles of trapped ancient atmospheric air.

Ice core records from Greenland and Antarctica stand out among other palaeoclimatic records as having the highest stratigraphical integrity, the highest temporal resolution, the only direct sequence of atmospherically deposited chemical substances and isotopes back in time. Moreover they are the only direct source of pre-industrial greenhouse gas records. Ice cores also offer an independent time control of climatic events since ice cores may be dated independently, meaning that the dating does not have to rely on radiocarbon dating or correlation with variations in orbital forcing.

2. Direct and indirect climate data from ice cores

Climate data may in general be split into two categories; indirect or proxy data and direct climate data. Only few of the measurements performed on ice cores actually record the climate directly. The direct climate records are e.g. the accumulation record of the ice and the borehole temperature.

2.1 Direct climate data

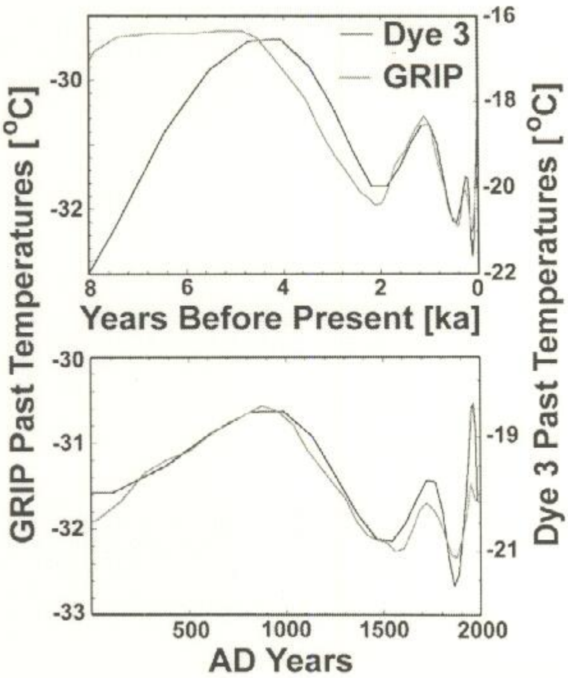
2.1.1 The accumulation record

In the accumulation zone of an ice cap, where no or only minor summer melting occurs the precipitation falling on the ice is conserved and slowly transformed into ice during firnification. Through identification of the annual cycle in other components of the ice the annual accumulation and its yearly variations may in this way be directly determined from ice cores.

2.1.2 The borehole temperature

Temperature measurements from a deep ice core bore hole reveal a history of past surface temperatures. In the central parts of the large ice sheets, where only little melting occurs, the surface temperature of the ice equilibrates with the surface air temperature. Through the combined heat and ice flow the temperature signal propagates down through the ice, and the vertical temperature profile of the ice cap may thus supply a direct measure of prehistoric air temperature. As the temperature is slowly transferred through the ice fast temperature fluctuations are readily damped, but longer term variations are stored for several thousand years. The seasonal temperature signal thus disappears a few meters below the snow surface, but the longer lasting temperature variations of the last millenium, such as the little ice age and the medieval warm period may still be identified (Figure 3). Even the very cold ice age temperatures clearly evolve from the temperature reconstruction. These measurements thus provide a direct record of ice surface temperatures.

Figure 3 Past temperature variations extracted from the GRIP and Dye 3 bore hole temperatures (Figure from Dahl-Jensen et al., 1998). The temperature reconstruction was performed using inverse Monte Carlo methods. The upper plot displays temperature variations over the past 8,000 yrs, whereas the lower plot is a zoom on the past 2,000 yrs. Similar temperature variations for the last 2,000 yrs have been reconstructed from Law Dome bore hole data from Antarctica.



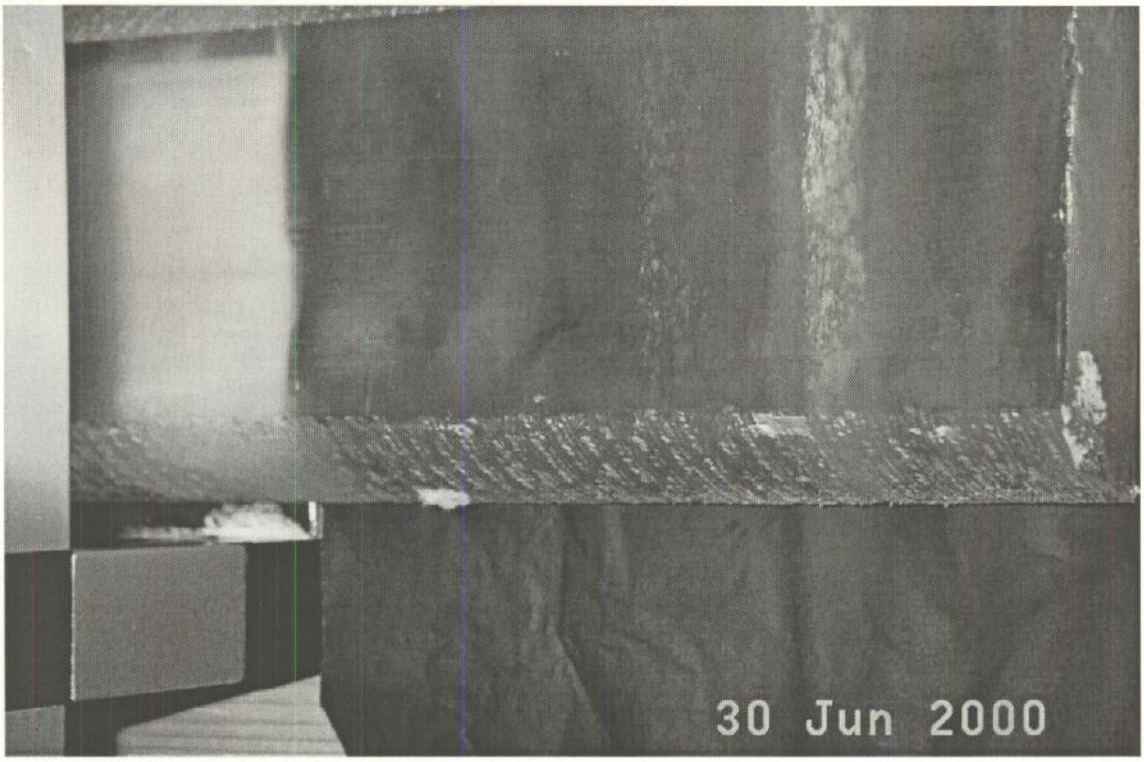
2.1.3 Greenhouse gases

A third type of direct climate indicators from ice cores are the records of the concentration of e.g. greenhouse gases which are trapped in tiny air bubbles enclosed in the ice. From these records the low atmospheric CO_2 content of the ice age climate of about 180 ppm and the increase over the past century from a pre-industrial value of about 280 ppm to the current value of about 380 ppm were first recognised (Figure 5). In the past years the greenhouse gas records from different ice cores have become a very valuable tool for synchronisation of different ice cores. This will be further discussed in Section 5.

2.2 Climate proxies

Most of the records obtained from ice cores are proxies of the actual climate. The climate indicator from ice cores most commonly referred to is without doubt the $\delta^{18}O$ signal, which is a temperature proxy. Due to different vapour pressure water molecules containing the two different oxygen isotopes fractionate during evaporation and condensation. This means that the isotopic ratio of a precipitation sample reflects the history of evaporation and condensation. Given that the main conditions of transportation have been constant over time, samples taken from the same location thus reflect past cloud temperatures. These conditions are not necessarily valid over large scale climate changes, e.g. glacial-interglacial transitions. This means that it has been necessary to "re-calibrate" the isotopic thermometer for the glacial periods, and that quantification of temperature changes during transitions is not unambiguous.

Figure 4 *One of the rare visible ash layers in the NGRIP ice core. This ash layer is connected to the Z2 volcanic eruption about 70,000 yrs BP.*



Besides $\delta^{18}O$ many different parameters such as different ions, the electrical conductivity, insoluble dust particles, and physical ice properties have been measured on ice cores over the past decades. While these parameters are not direct climate indicators, their intensities and variations may reveal information on e.g. atmospheric circulation changes and volcanic events. Major volcanic eruptions may sometimes be identified through the occurrence of visible ash layers in the ice (Figure 4), in many cases however ash particles have not been transported all the way to the remote ice sheets. Still, volcanic eruptions are readily identified through strongly acidic layers in the ice accompanied by high levels of sulfate and sometimes chloride or flouride. The exact chemical signal depends on the specific volcano. Besides the volcanic eruptions chemical species recorded in the ice cores derive from other sources such as sea salt, mineral dust, biological processes, and their concentrations vary both over a seasonal cycle and on climatic time scales. Long term variations of these quantities may reveal information about storminess, ice cover, biological activity, transportational and depositional processes.

3. Dating of ice core strata

Detailed measurements of the stable isotopic composition in ice cores may reveal seasonal cycles, i.e. consecutive layers of winter and summer snow. In general a conservation of the seasonal cycle can only be expected when the annual snowfall exceeds 250 mm water equivalent per year and the layers are not so deep and old that diffusion of the isotopes and the thinning by ice flow have obliterated the ice stratigraphy. These conditions are fulfilled for several Greenland locations, and a few coastal sites in Antarctica. Dating of ice cores then becomes equivalent to tree ring dating, and annual layers may simply be counted from the top of the core. So far counting of the isotopic strata has been done more than 4,000 years back in Greenland.

Several chemical components, such as sulfuric acid, nitric acid, sea salt, calcium carbonate and insoluble dust also display seasonal cycles. These components do not diffuse and become obliterated with depth or age in the same way as the stable isotopes. Absolute dating using the chemical components may thus be extended further back in time than the stable isotopes allow for, and seasonal cycles have been observed in ice more than 40,000 years old. In the future there is a possibility to continue absolute dating through the last ice age (100,000 years) at proper locations with new experimental techniques. So far, the termination of the last ice age has been dated to 11,550 years B.P. ± 70 years in the Greenland GRIP core using a combination of stable isotopes and chemical components. The Greenland GISP2 core has been dated down to 40,000 years by counting visible cloudy bands which is a physical manifestation of the variations in the concentration of chemical components.

Dating of Greenland ice older than 40,000 years and dating of most Antarctic ice cores is done through ice flow modelling. The accuracy of this dating is highly dependent on how well past rates of accumulation can be estimated. Dating obtained this way is not absolute; but due to the relatively simple ice flow at many of the chosen ice core locations the accuracy obtained in this way may be much better than for many other palaeoclimatic records.

As described in Section 2.2. tracers from volcanic eruptions may be found in ice cores and a whole suite of historically known volcanic eruptions have been identified in this way. This offers a good check on ice core dating as well as an estimate of the magnitude of the eruptions. Pre-historic eruptions can be used as time markers for comparison of ice core strata with deep ocean and terrestrial sediments where the dating is much less certain. By employing element analysis of the few volcanic ash particles in ice cores a "fingerprint" of specific eruptions may be obtained.

Dating of Antarctic ice cores down to 40,000 years B.P. is normally done by a combination of ice flow modelling and synchronisation with Greenland dating, using volcanic eruptions found in both hemispheres and fast variations in the greenhouse gas, methane.

4. The last glacial period and fast climate variations

The fast climate variations identified in the glacial part of the Greenland ice cores (Figure 2) are characterised by sudden shifts between two climatic stages. The periods of warmer glacial climate are called Greenland isotope inter-stadials, also known as Dansgaard/Oeschger cycles (D/O cycles), and 24 such cycles are registered. The cold periods are called Greenland isotope stadials. Although the duration of the inter-stadials is highly variable they all display similar features. Most of them are clearly "saw tooth shaped", i.e. they represent a sudden shift from cold to warmer climate followed by a gradual cooling and an eventual temperature drop.

From Figure 2 it may furthermore be noted that the low $\delta^{18}O$ baseline is gradually declining throughout the glacial period. It appears that Greenland isotope stadial 1 (also known as Younger Dryas) and inter-stadial 1 (known as Bølling-Allerød) are D/O cycles overlaid on the gradually shifting baseline from the glacial period to the Holocene. It is thus plausible that at least two different mechanisms are responsible for climate changes during the glacial period.

Timeseries analysis performed on the isotope record tells us that the gradual baseline changes can partly be explained by variations in the Earths orbital parameters, i.e. the Milankovich climate forcing. The very low frequency spectrum contains components comparable to those of the Earths orbital parameters, but the D/O cycles cannot be explained this way.

During a D/O cycle most glaciological parameters change. Concurrent with the sudden warmings the concentration of sea salt, nitrate and sulfate drops by a factor of 3 to 5. The concentration of magnesium, calcium and dust drops by a factor of 10 to 100. At the end of the warm cycle the concentrations increase back to full glacial levels. Part of the concentration changes may be explained by increased precipitation during the "warm" part of the cycle, which leads to dilution of the impurities. However, precipitation rates changed by less a factor of 3, which is lower than the increase of the terrestrial components, magnesium, calcium and dust. The atmospheric loading of continental impurities over Greenland must thus have been higher during the cold periods. This increase was probably caused by a combination of climate changes in the source areas (implying e.g. vegetation changes), changes in atmospheric circulation and less wash-out by precipitation during transportation to Greenland caused by the generally drier atmosphere.

The concentration of the greenhouse gas methane also varies during the D/O cycles. Methane concentrations increase abruptly together with the Greenland $\delta^{18}O$ signal at the beginning of an inter-stadial and then revert back to lower levels at the end of the inter-stadial.

Paradoxically concentration changes in methane and other parameters occur simultaneously with changes in Greenland ice $\delta^{18}O$ - at least with the present temporal resolution. There are no leads and lags and thus no indication that methane played an active role in initiating the D/O cycles. The variations appear to be effects of D/O cycles rather than causes. With the present temporal resolution in ice cores the very strong correlation between $\delta^{18}O$, impurities and greenhouse gases makes the study of causes and effects difficult. It appears however, that the very swift climate change at the end of the last glaciaton, i.e. in less than 5 years is not unique, most of the D/O cycles display comparably abrupt changes.

5. Greenhouse gasses in ice cores

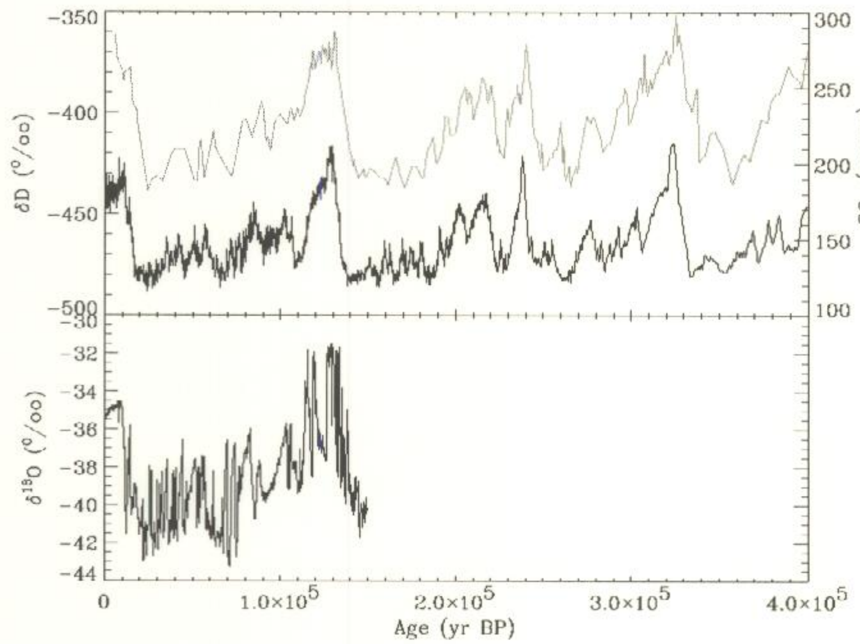
The longest and oldest ice core record to date is the Antarctic Vostok ice core, which is more than 4 km long (Figure 5). Due to the very low accumulation the annual layers are very thin, and the ice at the bottom of the Antarctic ice sheet is thus very old. The Vostok ice core covers four climatic cycles corresponding to more than 400,000 years. Compared to this the oldest layers so far identified in the Greenland GRIP record are about 120,000 years old. However, due to the higher accumulation rate in Greenland a much more accurate dating is possible for Greenland ice cores than Antarctic ice cores. As mentioned earlier, samples of atmospheric air are captured in tiny bubbles in the ice sheets. Over the upper hundred meters or so, air may diffuse freely within the snow and firn, and the wind may act to "pump" fresh air into the firn layer. As the snow is transformed to ice the air is however trapped in small bubbles. This means that gas samples extracted from an ice core are always somewhat younger than the surrounding ice. This gas-ice age difference depends on different quantities such as accumulation rate and temperature. In Greenland where the annual accumulation is relatively high the age difference only amounts to at most a few hundred years, but in

Antarctica, which includes the driest places on earth it may be several thousand years.

Air bubbles trapped in ice cores give a possibility to retrieve records of past atmospheric concentrations of e.g. greenhouse gasses. CO_2 and CH_4 are wellmixed in the atmosphere, and variations in their concentrations occur synchronically all over the globe. This fact has in recent years become a very valuable tool for synchronisation of Greenland and Antarctic ice cores.

Unfortunately however, due to the higher temperatures and impurity concentrations in Greenland ice in situ production of CO_2 may occur, and the measurements can not be trusted. Synchronisation of Greenland and Antarctic ice cores over the last glacial cycle have however been performed using high resolution methane measurements. The methane concentration changes abruptly in phase with the D/O cycles and the records from Greenland and Antarctic cores may be synchronised with an accuracy of about 200 years for depths displaying abrupt changes. In this way the temporal evolution of climate changes in the two hemispheres have been correlated with high accuracy. It has been found that the warming in the inter-stadials as recorded in the Greenland ice cores is generally preceeded by Antarctic warming by about 1,000 yrs, and relatively small increases in CO_2 apparently occur together with the Antarctic warming. Fast variations in CH_4 during the last glaciation on the other hand occur concurrently with Greenland $\delta^{18}O$ variations. The Vostok record has moreover shown that the pronounced sawtooth behaviour of the temperature record is also found for CO_2, but the decreases in CO_2 lag the temperature decreases by several thousand years.

Figure 5 Top: The deuterium (black, a temperature proxy) and CO_2 (green) records from the Vostok ice core (after Petit et al., 1999). Bottom: The GRIP $\delta^{18}O$ record in 200 years resolution.



6. The Eemian

The Eemian is the previous warm period, which lasted for about 20,000 years and ended approximately 110,000 years ago. In the GRIP and GISP2 ice cores, which were drilled 1990 – 1993, a high degree of correlation was found for the climate records of the past ~ 120,000 years. However, below this point the stratigraphic sequence of the Eemian ice in either one or both of these cores has probably been disturbed due to ice flow features close to bedrock. Nevertheless, there is an indication that the fast climate fluctuations of the last glacial period also occurred during the Eemian. The Eemian period is also covered by the Antarctic Vostok ice core, but as the glacial fast climate variations are clearly most pronounced for the North Atlantic area this record is not necessarily representative of Northern Hemisphere climate variability. Some ocean cores from the North Atlantic have shown fast fluctuations during the Eemian, but different cores display large differences.

In general, the question of an unstable Eemian climate is still unsolved. In the past years a new Greenland ice core record, the North GRIP record has been drilled with the aim of obtaining undisturbed ice layers from the Eemian period. The drilling will be finished in the fieldseason of 2001, where Eemian ice should be recovered.

7. Use of atmospheric models for the interpretation of the climate signal in ice cores

As many of the measurements performed on ice cores provide records of climate proxies it is most important to have a good understanding of these proxies. $\delta^{18}O$ has long been used as a temperature proxy for ice cores and investigations of the present day spatial and temporal relationship between temperature and $\delta^{18}O$ show a high degree of correlation. Nevertheless, when comparing the past temperature history from borehole measurements with the $\delta^{18}O$ record a disagreement between the two temperature estimates was found. The glacial-interglacial temperature change as recorded by the borehole temperature (~26 °C) was much higher than what had first been derived from the $\delta^{18}O$ record (12-13 °C), and the isotopic thermometer had to be recalibrated for the last glacial period. Three dimensional atmospheric general circulation models incorporating the different evaporation and condensation processes for the different oxygen isotopes have later revealed that part of the disagreement may be due to changes in the seasonal distribution of precipitation between the different climatic periods.

Atmospheric dust has long been thought to be a climate proxy relatively easy to understand. Since mineral dust particles derive only from continental surfaces and they are mostly insoluble and hardly involved in chemical reactions their variations should be relatively easy to explain. Nevertheless, even to simulate the correct amounts of dust transported to the different ice sheets under present day and LGM conditions has proven very difficult. It was only after isotopic provenance studies that the main source areas of dust transported to Greenland and Antarctica were determined. However, once the processes determining the large and abrupt variations in dust concentrations are understood, this understanding will be very valuable for estimating e.g. the influence of high glacial dust levels on the radiation balance, potentially an important feedback mechanism of the climate system.

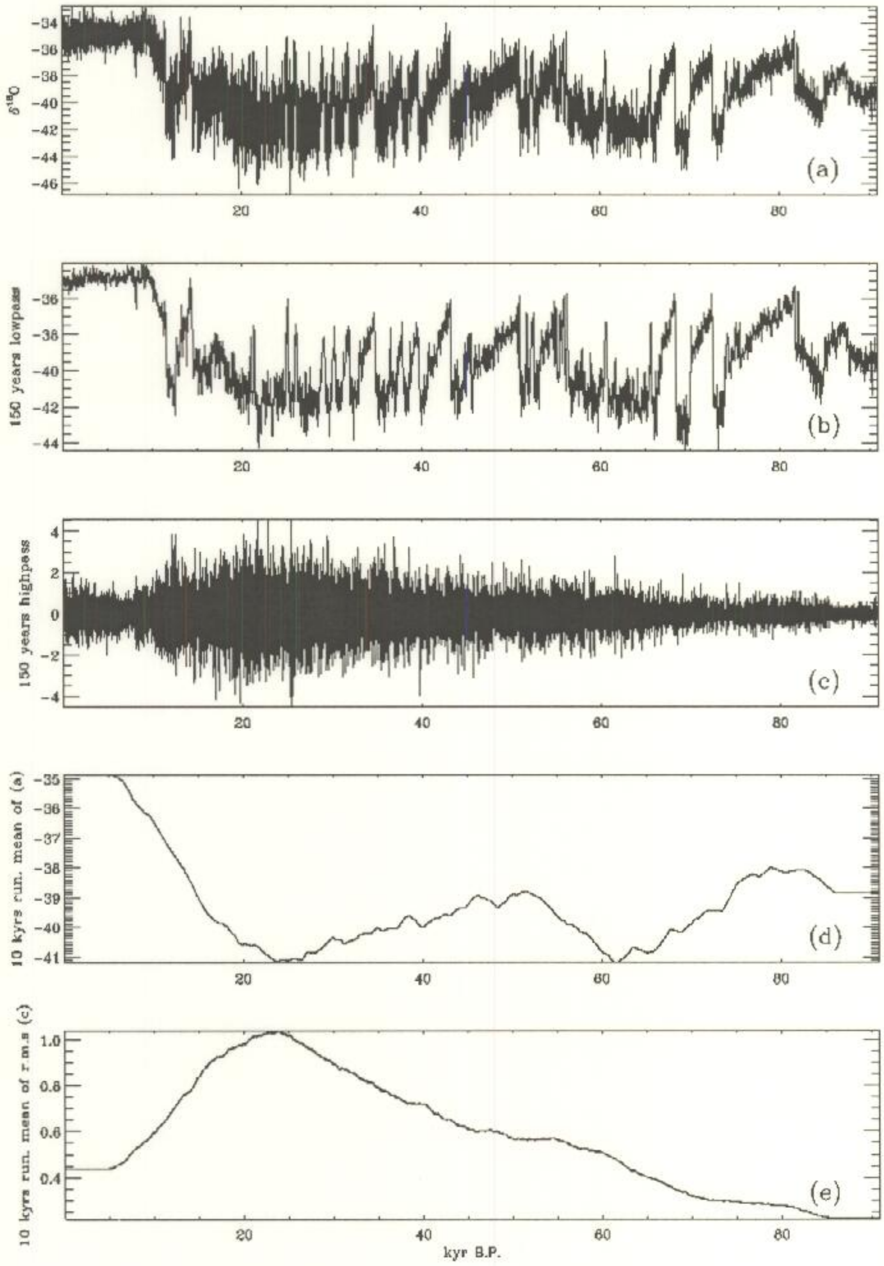
For many other climate proxies a thorough understanding of the processes behind the proxy also has to rely on models. Measurements and atmospheric modelling in combination may thus, as described above, significantly improve the understanding of climate proxies.

8. Climate dynamics and statistics derived from ice core records

An essential part of estimating the human influence on climate change is the evaluation of the natural variability of the climate itself. The ice core records show indisputably very rapid and large climate changes in pre-historical times. Since the records are obtained with very high temporal resolution and a precise dating, it is possible to extract information on various components of the climate system and to contrast different periods.

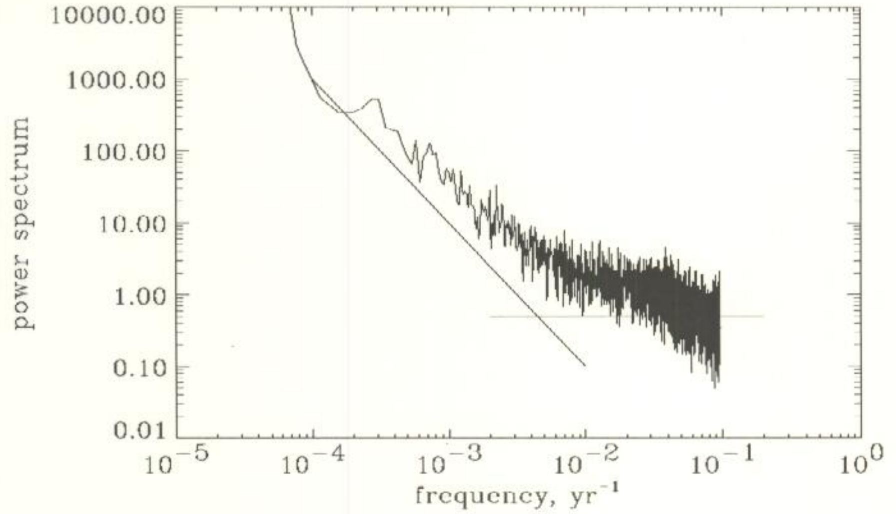
The present climate is, in comparison to the climate of the last glacial, relatively stable. The abrupt changes in temperature on time scales of a few hundred years in the last glacial period, the D/O cycles, are associated with surges from the large ice sheets and are probably due to changes in the North Atlantic Ocean circulation. The presence of the much larger ice sheets also impacts the atmospheric dynamics in glacial times. By comparison of very high temporal resolution ice core records, covering the Holocene and the last glacial period, we are able to observe differences in the atmospheric dynamics between the two periods.

Figure 6 *(a) The very high resolution $\delta^{18}O$ signal from the GRIP ice core. (b) The 150 years low pass signal of (a) showing the D/O oscillations. (c) The residual high pass signal, which is the difference between (a) and (b). (d) is the 10 kyrs running mean of (a), (e) is the 10 kyrs running mean of the root mean square of (c).*



The ice core data analysed in the following, and shown in Figure 6 (a), cover the Holocene and the glacial period with a temporal resolution ranging from seasons in the present to approximately 10 years at 91 kyrs BP (17,496 points). The data are based on sampling slices of specified increments down through the ice core and the power density spectrum is shown in Figure 7.

Figure 7 The power density spectrum of the $\delta^{18}O$ signal in Figure 6(a).



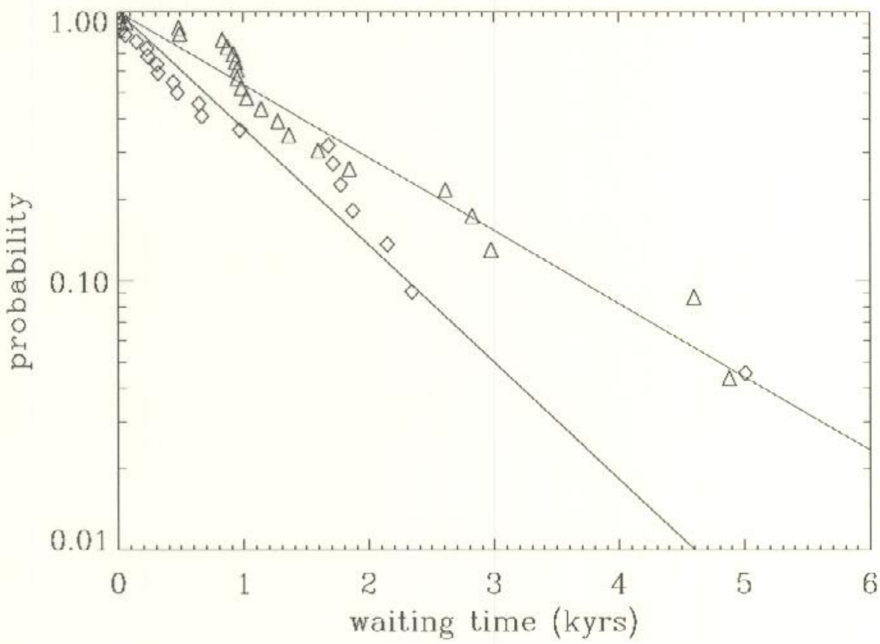
There are two regimes of behaviour in the power spectrum separated at around a few hundred years. For time scales longer than 100 - 200 years the spectrum is a continuous red noise spectrum without dominant peaks, signifying correlation over long time scales. For time scales shorter than 100 - 200 years the spectrum is a white noise spectrum, signifying short term or no temporal correlation. In order to separate the climate information of these two regimes we split the signal in the high- and the low frequency regime using a spectral cut at 150 years. Figure 6 (b) shows the 150 years low-pass, and (c) the high-pass signal.

The low-pass filtered signal contains the characteristic "saw-tooth" D/O cycles and the climate dynamics of these events is related to changes in the ocean circulation. The residual high-pass signal, Figure 6 (c), represents time scales faster than a few hundred years. This part of the signal contains information on atmospheric dynamics and atmosphere-ocean couplings on ENSO (El Nino - Southern Oscillation) time scales. The most striking feature of this signal is that the envelope of the fluctuations is related to the degree of glaciation - or the temperature as represented by the $\delta^{18}O$ itself. Figure 6 (d) shows the 10 kyrs running mean of $\delta^{18}O$ [6 (a)] and Figure 6 (e) shows the 10 kyrs running mean of the absolute value of the high-pass signal [6 (c)]. Besides the locally colder temperatures over the ice during the cold glacial periods, the lower $\delta^{18}O$ values may also be interpreted as a southward movement of the storm tracks. This implies a longer transport route for the precipitation thus increasing the depletion of ^{18}O. From this we interpret the increased variance as a direct result of a more stormy - or turbulent - state of the atmospheric flow during last glacial maximum (LGM).

Due to the presence of the ice sheets and a substantially colder northern ocean in the glacial period increased thermal gradients between equator and the high latitude glaciers are expected. This implies a more energetic and turbulent atmosphere through increased baroclinic activity in the glacial climate. This spectral analysis of the ice core isotope record is the first observation of changes in the atmospheric circulation from palaeoclimatic records for the LGM. It confirms atmospheric general circulation model (AGCM) studies of the LGM climate indicating that the atmosphere was in a state characterized by more storminess and more variability.

The triggering mechanism for the sudden climate changes characterising the D/O-cycles is not known today, but it is probably random fluctuations of the atmospheric forcing on the ocean circulation. This can be observed in the distribution of the waiting times between jumps from one climatic state to the other. Figure 8 shows the distribution function for the waiting time for jumping. The waiting time for jumping from the cold stadial to the warm inter-stadial and the waiting time for jumping the other way both have an exponential distribution. The upper straight line is an exponential with a mean waiting time of 1.6 kyrs corresponding to jumping from stadial to inter-stadial (triangles). The lower straight line is an exponential with a mean waiting time of 1 kyr, appropriate for jumping from inter-stadial to stadial. An exponential waiting time means that with chaotic atmospheric forcing there is no memory of how long time the system has spent in one state before jumping to the other, and it confirms that random fluctuations may cause the changes. Such a process is called a Poisson process.

Figure 8 The distribution of the waiting time, as calculated from GRIP calcium data. The jumping between the glacial and inter-stadial states is well described as a Poisson process. The waiting times are defined as the times between up and down crossings of the 300 years running mean through the level log(Ca) = 0.8 which separates the glacial and inter-stadial states. The waiting times have an exponential distribution.



The remarkable difference between the cold stadial and the warmer inter-stadial climate of the D/O-cycles is most probably closely connected to variations in the thermohaline circulation. Climate models of varying complexity from simple to fully coupled ocean-atmosphere general circulation models now more or less reliably reproduce the present and the LGM climate. However, at present the models are not capable of identifying the mechanisms responsible for the climatic changes observed in the records. Analyses of the GRIP calcium signal have inferred that the triggering mechanism for the observed for climatic changes may be single single extreme events. These events are related to ocean-atmosphere dynamics on annual or shorter time scales and could indicate a fundamental limitation in predictability of climate changes, in that they are fundamentally unpredictable and never captured in present days numerical circulation models. All coupled general circulation models will due to smoothening and coarse resolution almost certainly show gaussian statistics, and thereby underestimate extreme events. This could explain why these models have yet never succeeded in simulating shifts between climatic states.

9. Summary

Ice cores from Greenland give testimony of a highly variable climate during the last glacial period. Dramatic climate warmings of 15 to 25 °C for the annual average temperature in less than a human lifetime have been documented. Several questions arise: Why is the Holocene so stable? Is climatic instability only a property of glacial periods? What is the mechanism behind the sudden climate changes? Are the increased temperatures in the past century man-made? And what happens in the future?

The ice core community tries to attack some of these problems. The NGRIP ice core currently being drilled is analysed in very high detail, allowing for a very precise dating of climate events. It will be possible to study some of the fast changes on a year by year basis and from this we expect to find clues to the sequence of events during rapid changes. New techniques are hoped to allow for detection of annual layers as far back as 100,000 years and thus a much improved time scale over past climate changes. It is also hoped to find ice from the Eemian period. If the Eemian layers confirm the GRIP sequence, the Eemian was actually climatically unstable just as the glacial period. This would mean that the stability of the Holocene is unique. It would also mean, that if human made global warming indeed occurs, we could jeopardize the Holocene stability and create an unstable "Eemian situation" which ultimately could start an ice age.

Currently mankind is changing the composition of the atmosphere. Ice cores document significant increases in greenhouse gases, and due to increased emissions of sulfuric and nitric acid from fossil fuel burning, combustion engines and agriculture, modern Greenland snow is 3 - 5 times more acidic than pre-industrial snow. However, the magnitude and abruptness of the temperature changes of the past century do not exceed the magnitude of natural variability. It is from the ice core perspective thus not possible to attribute the warming of the past century solely to the influence of mankind. The climate changes recorded by meteorological observations since 1875 are not unique in climate history. Taking into account that the period around 1875 appears to have been one of the coldest during the Holocene makes it even more difficult.

Although the present situation is different from the past, we still need to understand past climatic changes in order to not only assess the effects of human activity but also to make better predictions of possible future natural climatic changes. The ice core community will continue to try to unravel the story of past climate changes - this is our challenge.

Further reading

Andersen, Katrine K., Alexandre Armengaud, and Christophe Genthon, 1998: Atmospheric dust under glacial and interglacial conditions. *Geophysical Research Letters* 25 (13): 2281-2284.

Barnola, J.M., D. Raynaud, Y.S. Korotkevich, and C. Lorius, 1987: Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* 329: 408-413.

Blunier, T., J. Chappellaz, J. Schwander, A. Dällenbach, B. Stauffer, T.F. Stocker, D. Raynaud, J. Jouzel, H.B. Clausen, C.U. Hammer, and S.J. Johnsen, 1998: Asynchrony of Antarctic and Greenland climate change during the last glacial period. *Nature* 394: 739-743.

Dahl-Jensen, D., K. Mosegaard, N. Gundestrup, G.D. Clow, S.J. Johnsen, A.W. Hansen, and N. Balling, 1998: Past temperatures directly from the Greenland Ice Sheet. *Science* 282: 268-271.

Dansgaard, Willi, H.B. Clausen, N. Gundestrup, C.U. Hammer, S.J. Johnsen, P.M. Kristinsdottir, and N. Reeh, 1982: A new Greenland deep ice core. *Science* 218 (4579): 1273-1277.

Dansgaard, Willi, S.J. Johnsen, H.B. Clausen, D. Dahl-Jensen, N.S. Gundestrup, C.U. Hammer, C.S. Hvidberg, J.P. Steffensen, A.E. Sveinbjörnsdottir, J. Jouzel, and G. Bond, 1993: Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* 364 (6434): 218-220.

Ditlevsen, P.D., 1999: Observation of -stable noise induced millenial climate changes from an ice-core record. *Geophysical Research Letters* 26 (10): 1441-1444.

Ditlevsen, P.D., H. Svensmark, and S. Johnsen, 1996: Contrasting atmospheric and climate dynamics of the last-glacial and Holocene periods. *Nature* 379: 810-812.

Fuhrer, K., E.W. Wolff, and S.J. Johnsen, 1999: Timescales for dust variability in the Greenland Ice Core Project (GRIP) ice core in the last 100,000 years. *Journal of Geophysical Research* 104 (D24): 31043-31052.

Hammer, C., P.A. Mayewski, D. Peel, and M. Stuiver, 1997: Preface. *Journal of Geophysical Research* 102 (C12): 26315-26316.

Hammer, C.U., H.B. Clausen, Willi Dansgaard, N. Gundestrup, S.J. Johnsen, and N. Reeh, 1978: Dating of Greenland ice cores by flow models, isotopes, volcanic debris, and continental dust. *Journal of Glaciology* 20: 3-26.

Indermühle, A., T. F. Stocker, F. Joos, H. Fischer, H. J. Smith, M. Wahlen, B. Deck, D. Mastroianni, J. Tschumi, T. Blunier, R. Meyer, and B. Stauffer, 2000: Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica. *Nature* 398: 121-126.

Johnsen, S.J., Willi Dansgaard, H.B. Clausen, and C.C. Langway, Jr., 1972: Oxygen isotope profiles through the Antarctic and Greenland ice sheets. *Nature* 235 (5339): 429-434.

Petit, J.R., J. Jouzel, D. Raynaud, N.I. Barkov, J.-M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V.M. Katlyakov, M. Legrand, V.Y. Lipenkov, C Lorius, L. Pépin, C. Ritz, E. Saltzman, and M. Stievenard, 1999: Climate and atmospheric history of the past 420,000 years from the vostok ice core, Antarctica. *Nature* 399: 430-436.