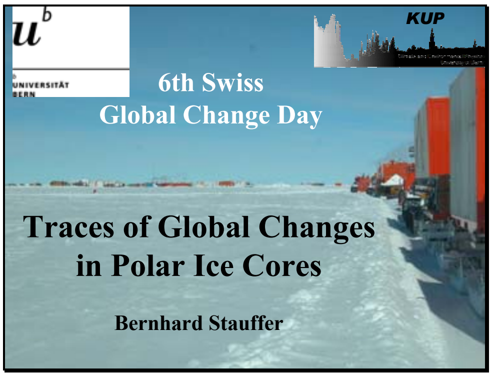
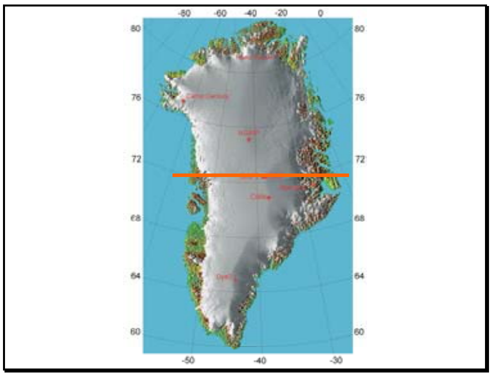
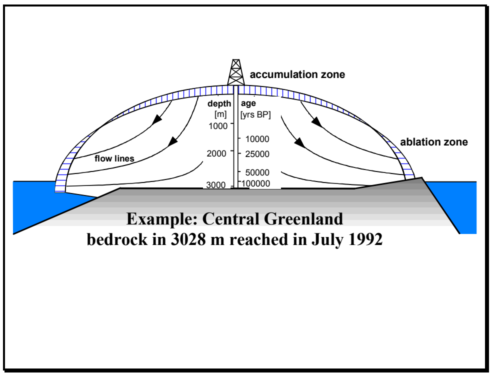


The goal of the analyses of polar ice cores, is to investigate the mechanisms of global climatic changes. Polar ice cores are especially well suited for this purpose because they allow, beside a lot of other information, to reconstruct the evolution of the local temperature as well as of the atmospheric concentration of greenhouse gases.



The map shows the Greenland ice sheet. Deep drillings have been performed at Camp Century (1967), Dye 3 (1981) GRIP (1992) in the centre of the ice sheet and North GRIP (2003).

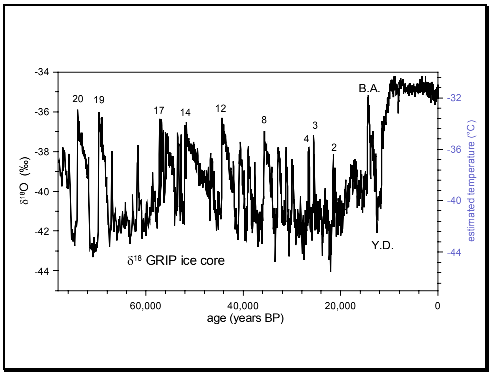
If we imagine to cut a slice of the ice sheet along the red line, it would look schematically as in the following sketch.



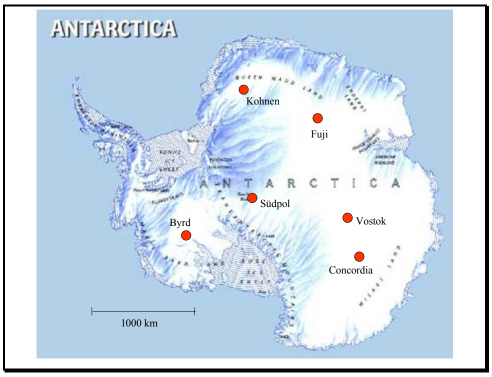
The vertical and horizontal scales are of course not the same. The east-west distance is about 800 km, the ice thickness "only" 3 km. Snow is accumulating in the central parts of the ice sheets, becomes compacted to firn and ice and the ice is covered by new snow falls and moving deeper and deeper into the ice sheet and flows slowly to the coast where it melts or breaks off as ice bergs. In equilibrium, mass and form of the ice sheet remain unchanged. Core drilling at the centre of an ice sheet provides a complete collection of the precipitation of about 100'000 years in Greenland and of up to 1 million years in Antarctica.

The Greenland Ice core Project, GRIP, reached bedrock in July 1992 in 3028 m depth below surface.

This figure shows one of these ice cores to be analysed, 10 cm in diameter and in average about 2.5 m long per run.

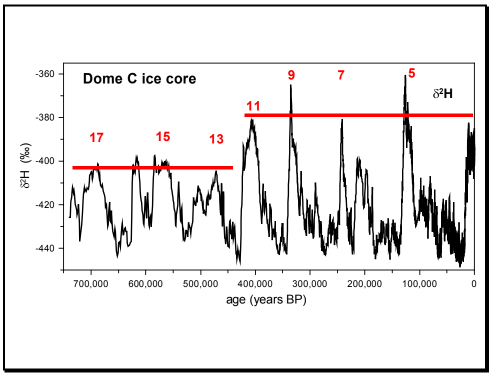


The stable isotope record, which is a measure of the local mean annual temperature, confirmed the presence of fast temperature changes during the last glacial epoch, so called Dansgaard/Oeschger events, which were suggested already by Dye 3 results. They will be discussed below after the discussion of glacial – interglacial cycles. The GRIP record shows only the last ice age and the Holocene. But in Antarctica ice cores can show several glacial cycles due to much smaller accumulation rates.

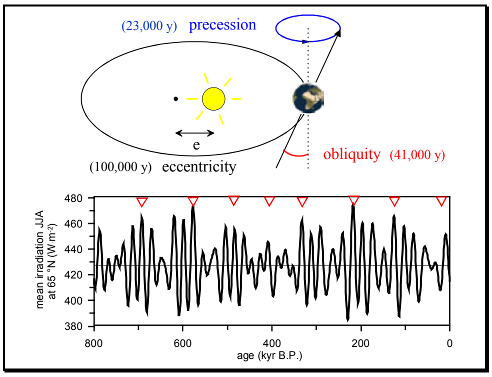


The Antarctic ice sheet is larger than the one from Greenland and if it would melt, sea level would rise about 80 m, if Greenland melts it would rise about 7 m. Deep core drillings were performed 1968 at Byrd by the US. Russia started 1980 a deep drilling at Vostok. Later France and the US collaborated in the deep drilling which reached finally in 1998 a depth of 3626 m. The ice at the bottom of the hole is about 420,0000 years old. A Japanese deep drilling at Dome Fuji reached a depth of 2,500 m in 1996.

Two drillings are performed recently in the frame of the European Project for Ice Coring in Antarctica (EPICA) in Dronning Maud land at Kohnen Station and at Dome C at Concordia Station. The drilling at Concordia reached the final depth of 3260 m beginning of 2005. The age of the ice at the bottom is estimated to be about 890,000 years.

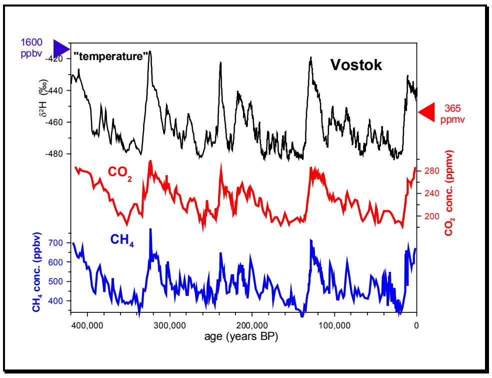


The δD-record along the core shows 8 glacial cycles. Interstadials are marked by odd numbers, so called Marine Isotope Stages (MIS). Every about 100,000 years there is one of these warm epochs, but there is quite a variety in the evolution of the individual interstadials. One interesting result is e.g. that the warm climatic epochs before 500,000 years B.P. have been less warm but generally of a longer duration. Especially interesting is stage 11 , which can be considered to some extent as an analogue to the Holocene.



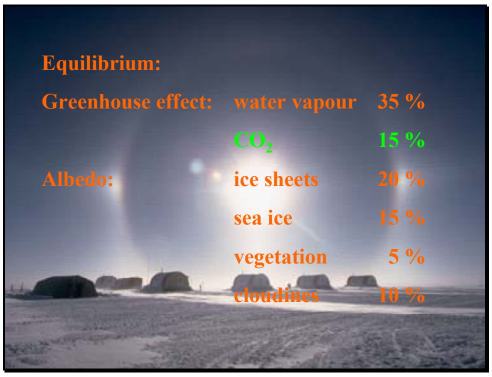
There is little doubt that the pacemaker for the appearance and disappearance of interstadials are the orbital parameters of the earth. The very small eccentricity of the orbit varies with a period of about 100,000 years. The polar axis is not perpendicular to the orbital plane but has an obliquity between 22 and 24.5°, varying with a periodicity of 41,000 years, and finally the polar axis is precessing around the perpendicular on the orbital plane, about once in 23,000 years.

This leads to a variation of the solar irradiance in function of latitude and season. Important for a deglaciation is the irradiation in high northern latitudes in summer. This record shows the mean irradiation in 65°N during June, July and August.

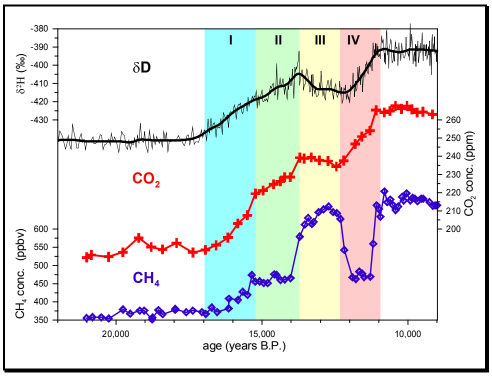


However, the changing solar radiation can only act as a trigger, it needs strong amplification factors for a deglaciation and for a global temperature increase of 3 – 5 °C. One important amplification factor is the greenhouse gas CO_2, while the CH_4 variations are rather a result of the climatic variations. The blue and red triangles indicate the present atmospheric concentrations.

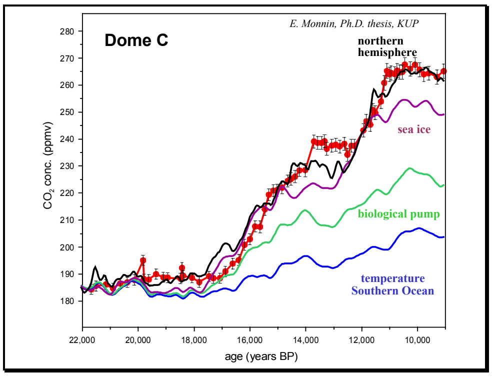
We will concentrate for the following the transition from the last glacial epoch to the Holocene.



According to model calculations the effects responsible for the temperature increase at the end of the last glacial epoch have been to 50 % greenhouse effects and to 50 % decreasing albedo. However, most of the effects are directly coupled to the temperature increase: as higher temperature as more humidity and smaller snow cover. Only for the CO_2 concentration a direct link with temperature variations is at least not obvious.



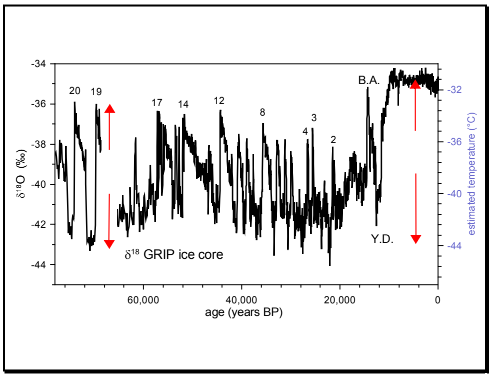
To investigate this link, we reconstructed the CO_2 increase during the transition from the last glacial epoch to the Holocene of the Dome C ice core in great detail. The almost simultaneous start of the temperature and CO_2 increase is a strong indication that the Southern Ocean played a key role, as was expected already. However, the fast increases between phase II and III and at the end of phase IV are most probably not caused by the Southern Ocean, but by some processes in the northern hemisphere.



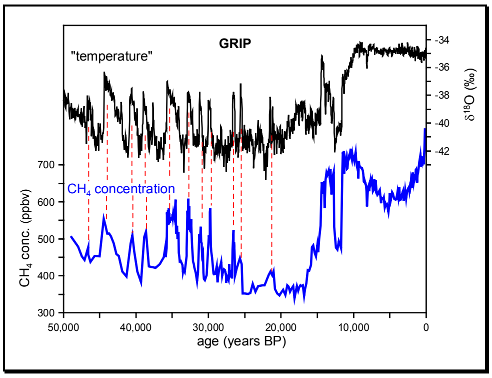
How is the Southern Ocean influencing the atmospheric CO_2 concentration? – If water becomes warmer less CO_2 is dissolved, as you know from beverages with CO_2. It is estimated that this effect is responsible for about 20 ppm of the 76 ppm increase. Eric Monnin assumed that this part of the increase occurred linear to the Antarctic temperature. Another cause is the biological pump in the S. Ocean. Carbonate is precipitating from the surface to the deep ocean, more if more iron and magnesium is available, as was the case during the ice ages (high dust concentrations).

The reduction of the biological pump could be responsible for another 20 ppm, and here he assumed that this part of the CO_2 increase was reverse linear to the evolution of the dust concentration measured along the Dome C ice core. There are other effects, like the stratification and the sea salt concentration of the ocean. Eric Monnin assumed that these effects are linearly related to the sea ice extent around Antarctica and responsible for another 20 ppm and that the Na concentration in ice cores is a good proxy for the sea ice extent.. Finally there are effects of the northern hemisphere, first of all also the surface temperature of the ocean and the biological pump, which are estimated to contribute about 16 ppm of the

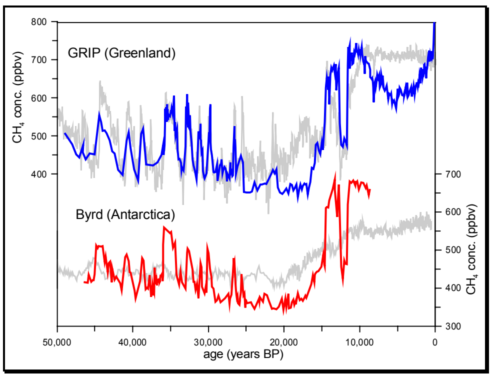
increase with an evolution linear to the Greenland temperature reconstructed from the GRIP ice core. This is, of course, not a model, but rather an intellectual game, but I hope that I could demonstrate how all the records of ice cores can be used to investigate such important questions.
Once we will know everything about this transition, the question will arise whether all transitions from ice ages to interstadials followed the same pattern.



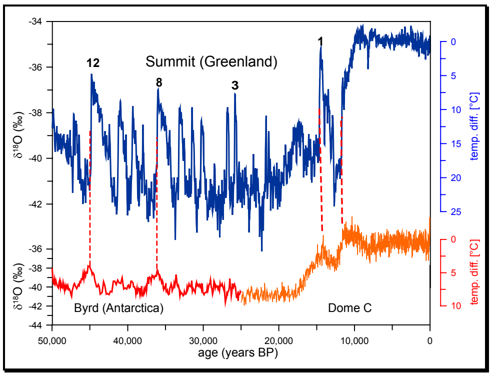
Lets turn now to the last glacial epoch with its fast climatic variations. The variations have been fast and drastic. The blue scale at right is a temperature estimate based on the assumption, that the isotope/temperature relation was the same as today. New analytical methods showed that this is not the case. The local temperature increase between glacial epoch and Holocene was not 12 °C but rather 20 °C. The temperature increase to D/O event 19 occurring in about 20 years, was 16 °C. But even such drastic and large changes would not be very exciting if they would be restricted to central Greenland.



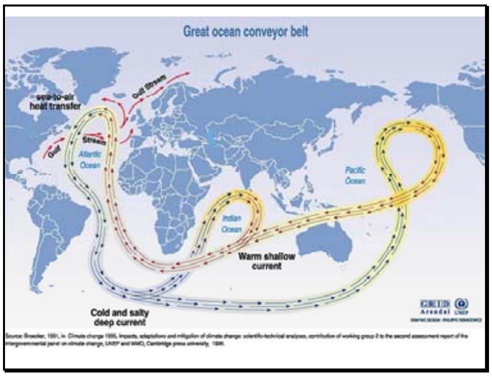
However, methane measurements along the same core showed that they are of a global significance. Why? - Pre industrial methane sources are mainly in low and mid latitudes, and a change of the methane concentration indicates that there were climatic variations, not necessarily great temperature changes but possibly changes in the amount of precipitation, in these regions.



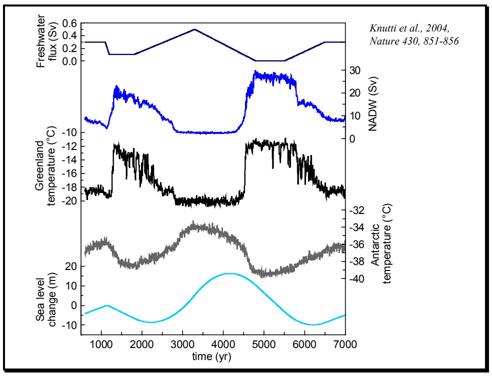
If the measured CH_4 concentration is global, because CH_4 is well mixed in the atmosphere, we expect in Antarctic ice cores the same evolution of the CH_4 records, which is indeed the case, as shown by the comparison of the blue record from Greenland and the red record from Byrd (Antarctica). The grey records indicate the temperature records which are quite different for Greenland and Antarctica.



CH_4 can even be used to get synchronised age scales. The synchronised records suggest an interesting result: at least the longest Dansgaard/Oeschger events have corresponding, when also smaller, signals in the Byrd record. However, the warming starts earlier and is by far not so fast as in Greenland. It reaches its maximum as soon as the abrupt warming in Greenland starts. This is a very important finding of ice core research.

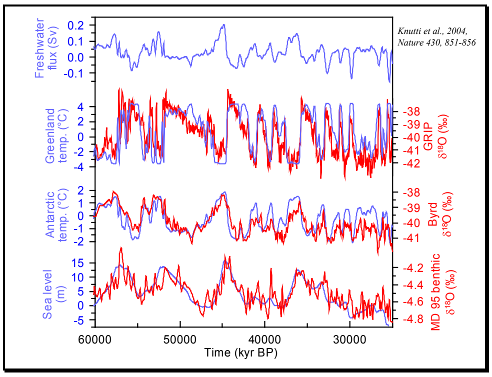


Responsible is the thermohaline circulation of the ocean. The picture shows W. Broeckers conveyor belt which explains simplified this circulation. Cold, salty and therefore dense water sinks in the North Atlantic to the bottom of the North Atlantic and flows southward where it is up-welling in different regions. The backflow is at the surface and transports heat from the Southern hemisphere especially to the North Atlantic region. If large fresh water masses are entering the North Atlantic, e.g. by breaking of large ice masses, the salt concentration of the surface water there decreases, the water is less dense and the conveyor belt less active ore even inactive.



Knutti and others used a coupled ocean-atmosphere-sea ice model to estimate quantitatively the effect of fresh water discharges into The North Atlantic Ocean. The model shall not be discussed but the most important results are summarised in this and the following figure. This figure shows changes forced by a schematic evolution of the freshwater discharge into the North Atlantic (top curve).

An increase diminishes or stops the North Atlantic Deep Water formation. This has a direct effect to Greenland temperature, which shows an abrupt warming at the time of the start of the NADW. Antarctic temperature is changing as well but with a smaller amplitude and with time lags which depends on the amplitude and the duration of freshwater discharges. The sea level is more or less just an integration of the s fresh water discharge.



The authors started now from the GRIP "temperature" record (red) and calculated backward the evolution of the fresh water discharge (top). Now they forced their model by this evolution of the discharge. The result concerning Greenland temperature (blue) is less detailed but correlates quite well as expected. Further the Antarctic temperature and the sea level was calculated (blue). These last two records can now be compared with measured results (red records) along the Byrd ice core concerning Antarctic temperature and on deep sea sediment records concerning sea level.

So you see that the model gives at least very consistent results. This is not a prove that it is correct, but it is quite convincing that it describes the most important mechanisms correctly.

There remains one important open question. Could such fast climatic changes also occur at present or after a substantial global warming. Model calculations show that it would be principally possible. However, to my knowledge we have no evidence from any paleo archive that fast changes occurred in an interstadial.