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Timing of the Antarctic Cold Reversal and the atmospheric CO_2 increase with respect to the Younger Dryas event

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Abstract. The transition from the Last Glacial to the Holocene is a key period for understanding the mechanisms of global climate change. Ice cores from the large polar ice sheets provide a wealth of information with good time resolution for this period. However, interactions between the two hemispheres can only be investigated if ice core records from Greenland and Antarctica can be synchronised accurately and reliably. The atmospheric methane concentration shows large and very fast changes during this period. These variations are well suited for a synchronisation of the age scales of ice cores from Greenland and Antarctica. Here we confirm the proposed lead of the Antarctic Cold Reversal on the Younger Dryas cold event. The Antarctic cooling precedes the Younger Dryas by at least 1.8 kyr. This suggests that northern and southern hemispheres were in anti-phase during the Younger Dryas cold event. A further result of the synchronisation is that the long-term glacial-interglacial increase of atmospheric CO_2 was not interrupted during the Younger Dryas event and that atmospheric CO_2 changes are not necessarily dominated by changes in the North Atlantic circulation.

Introduction

For an understanding of the transition from the Last Glacial (LG) before 15 kyr before present (BP) to the Holocene (present interglacial) it is essential to know the exact timing of the temperature increase in Antarctica relative to the temperature increase at high northern latitudes. The warming in the northern hemisphere is interrupted by the Younger Dryas (YD) event during which temperatures fell again to almost glacial levels for about 1 kyr [*Dansgaard et al.*, 1989]. Atmospheric cooling coincided with a reduction in sea surface temperature in the North Atlantic, most probably caused by reduced heat transport to northern latitudes due to lesser deepwater formation [*Broecker et al.*, 1985; *Oeschger et al.*, 1984; *Ruddiman and McIntyre*, 1981]. Although YD was strongest in that region, the decrease in the CH_4 concentration demonstrates that also the climate of wetland regions, which were mainly present in the tropics during this climatic period, were influenced [*Chappellaz et al.*, 1993].

In contrast to the strong YD signal in the northern hemisphere the isotopic records (δD and $\delta^{18}O$ which are proxies for temperature) from Antarctica show no abrupt changes for this period [*Jouzel et al.*, 1995; *Mayewski et al.*, 1996]. Instead, the glacial-interglacial warming occurs in two steps interrupted by a slightly colder period, the so called Antarctic Cold Reversal (ACR). It was proposed that the ACR preceded the YD by about 1 kyr [*Jouzel et al.*, 1995; *Sowers and Bender*, 1995].

CO_2 records from Antarctic ice cores are believed to be the most reliable because impurities, that could be responsible for in situ production of CO_2, are one order of magnitude less abundant than in cores from Greenland [*Anklin et al.*, 1997; *Delmas*, 1993]. The transition from the LG to the Holocene was associated with an increase of the atmospheric CO_2 concentration from approximately 200 to 280 ppmv [*Barnola et al.*, 1991; *Neftel et al.*, 1988] which is mainly driven by changes in the marine carbon cycle/ocean circulation [*Archer and Maier-Reimer*, 1994]. The dating uncertainty together with gaps in the Antarctic CO_2 record have led to speculations about fast CO_2 variations during YD [*Beerling et al.*, 1995]. Knowledge of the phase relation between various climate records from different locations is a prerequisite to understand the dynamics of the last transition and other climatic cycles during the ice age. Therefore it is important to link the CO_2 record to high-resolution proxy data derived from ice cores from both hemispheres.

Dating

In Antarctic ice cores (especially Central East Antarctica) the dating accuracy is limited due to the low accumulation rate which does not allow annual layer counting to greater depth [*Jouzel et al.*, 1995]. It is possible, however, to synchronise Antarctic ice cores to well-dated ice cores from Greenland using global parameters such as the isotopic signal of oxygen in air ($\delta^{18}O_{air}$) or methane (CH_4). Variations in $\delta^{18}O_{air}$ are rather slow and limit the accuracy of a synchronisation of the transition from LG to the Holocene between different ice cores to about ±600 yr [*Sowers and Bender*, 1995]. Particularly during periods of fast climatic change a better synchronisation is achieved by using a fast changing parameter. Methane shows significant variations from the LG to the present [*Blunier et al.*, 1995; *Chappellaz et al.*, 1993] of up to 250 ppbv in 200 yr (YD) resulting in a theoretical accuracy of the synchronisation of <50 yr. This estimate takes into account the data accuracy (20ppbv, 2σ) as well as the uncertainty for the CH_4 difference between Greenland and Antarctica (interhemispheric gradient) resulting from CH_4 sources located predominantly in the northern hemisphere. This dif-

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ference is 5-8% [*Chappellaz et al.*, 1997] during the Holocene but probably less in the glacial.

The CH_4 records from two Antarctic ice cores (Byrd Station 80°S, 120°W; Vostok 78.47°S, 106.80°E) are compared to a Greenland record (GRIP ice core, Summit 72.58°N, 37.64°W) over the period of the transition from the LG to the Holocene with respect to the coherence of the used time scales. The ice of the GRIP core has been dated stratigraphically with an uncertainty of ±200 yr during YD [*Johnsen et al.*, 1992]. The most accurate time scale for the Byrd core is obtained by the detection of annual layers of acidity. The dating uncertainty at the YD is ±500 yr [*Hammer et al.*, 1994]. The Vostok core has been dated with a glaciological model where the accumulation was deduced from the δD record [*Jouzel et al.*, 1993].

The $\delta^{18}O_{air}$ and CH_4 records can not directly be used to synchronise two ice cores, because the porous firn layer on the surface of the ice sheet is continuously exchanging air with the overlying atmosphere. Air, which gets enclosed in bubbles typically at 50 to 100 m below the surface, has a younger mean age than the age of the surrounding ice [*Schwander et al.*, 1997]. Let Δage denote the difference between the age of the ice and the mean age of the gas at close-off depth. Consequently two time scales have to be known 1) a time scale for the ice and 2) a time scale for the air, both of which depend on core site characteristics. The Δage uncertainty is identical for the $\delta^{18}O_{air}$ and the CH_4 method. However, the CH_4 method reduces significantly the uncertainty of the air time scales from Greenland and Antarctica.

Δage for GRIP and Byrd has been calculated using a dynamic model [*Schwander et al.*, 1997]. The determining parameters are accumulation rate and temperature. For Summit these parameters are well known [*Dahl-Jensen et al.*, 1993; *Johnsen et al.*, 1995] allowing the calculation of Δage to ±100 yr. The accumulation rate at Byrd Station was estimated based on measurements of annual layers [*Hammer et al.*, 1994]. The glacial-interglacial temperature increase in Antarctica is about 7°C based on the relation between $\delta^{18}O$ and temperature [*Robin*, 1983] but could have been up to 15°C based on recent borehole temperature measurements in east Antarctica [*Salamatin et al.*, 1997]. From this and the uncertainty in the accumulation rate which is probably <25% we estimate the uncertainty of Δage to ±100 yr back to 12 kyr BP increasing to ±200 yr at 14.5 kyr BP (where the doubling of the glacial-interglacial temperature difference increases Δage only by about 50 yr at 14.5 kyr BP). For the calculation of Δage at Vostok a model similar to the one used for GRIP and Byrd was used [*Barnola et al.*, 1991]. Temperature and accumulation were deduced from the δD record [*Jouzel et al.*, 1993]. For the calculation of Δage at Byrd Station and Vostok the heat transport in the firn was neglected which is justified by the rather slow temperature changes in Antarctica.

Fig. 1a shows the CH_4 results from the three ice cores. Comparing the Vostok to the GRIP record we see that the Vostok dating is about 1.2 kyr too young at the YD [*Chappellaz et al.*, 1993]. We calculated the sensitivity of the Vostok time scale on the accumulation rate [*Jouzel et al.*, 1993] and found that the best agreement between the two CH_4 records (with recalculation of Δage for the new accumulation) was obtained by decreasing the Vostok accumulation rate slightly (8%). Assuming an uncertainty of 2°C in temperature and 2% in accumulation the Δage uncertainty for Vostok is ±500 yr at the YD.

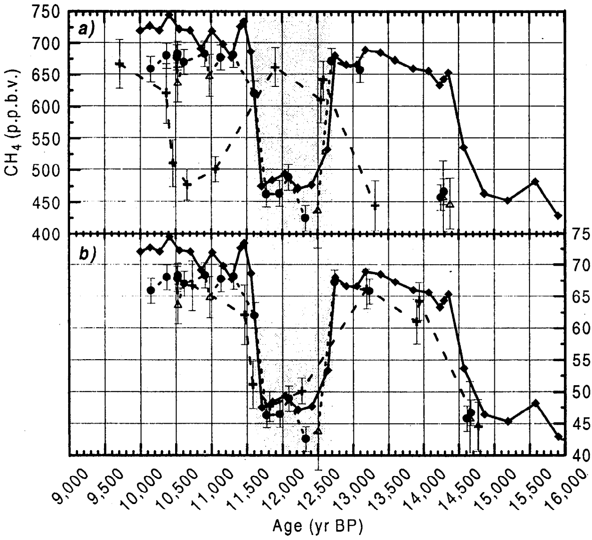

Figure 1. Methane concentrations from the GRIP, the Byrd, and the Vostok ice core a) each with its original time scale b) with the common time scale (see text). Diamonds: results from the GRIP ice core [*Chappellaz et al.*, 1993] with a few additional results during the Younger Dryas cold event (shaded). The 95% confidence interval is ±20 ppbv. Dots (new data) and open triangles [*Lochbronner*, 1989; *Stauffer et al.*, 1988] are results from the Byrd ice core with 95% confidence intervals. Crosses: results from the Vostok ice core [*Chappellaz et al.*, 1990] with one additional data point at 11.6 kyr BP. The CH_4 concentration in Antarctica is generally lower than in Greenland due to the CH_4 source distribution.

From the covariance of the GRIP and the Byrd signals we conclude that the time scales agree within ±100 yr at the end of the YD-Holocene transition. Unfortunately, between 14.3 and 13.1 kyr BP no ice from the Byrd core was at our disposal and a definitive link of the GRIP and the Byrd datasets prior to the YD was not possible. Nevertheless we can draw some conclusions comparing the concentration of the lowest datapoint in the Byrd core to the GRIP record. The CH_4 results from Byrd (about 460 ppbv) at around 14.3 kyr BP correspond most likely to the similarly low CH_4 values from GRIP at around 14.7 kyr BP which makes the Byrd time scale about 400 yr too young relative to the GRIP time scale at this depth. This estimate is based on a 8% interhemispheric gradient and is therefore a lower limit; a lower interhemispheric gradient enlarges this difference reaching up to 1.5 kyr in the case of no interhemispheric gradient. The shift does not result from the uncertainty in the gas age-ice age difference but has to be attributed to the ice age time scale. To compare the isotopic and the CO_2 signals (Fig. 2) we chose to apply the minimal 400 yr correction to stretch the Byrd time scale linearly between 12.5 and 14.5 kyr BP. The Vostok time scale was adjusted decreasing the accumulation rate by 8%. The CH_4 records from the three ice cores with adjusted dating of the Byrd and Vostok samples are plotted in Fig. 1b.

Discussion

The synchronisation with CH_4 leads to a relative uncertainty to the GRIP ice time scale of about ±150 yr for Byrd and ±500 yr for Vostok (about the uncertainty of the Vostok Δage). The Byrd to GRIP uncertainty at 14.5 kyr BP is difficult to judge without further data. The range of possible shifts

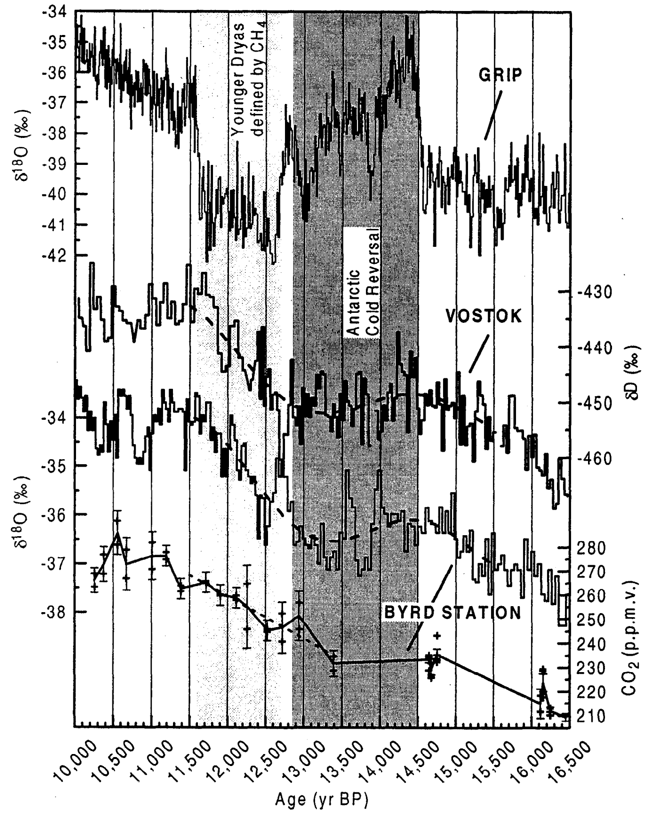

Figure 2. Isotopic records from the GRIP [*Johnsen et al.*, 1992] ($\delta^{18}O$), the Vostok [*Jouzel et al.*, 1993] (δD), and the Byrd [*Hammer et al.*, 1994] ($\delta^{18}O$) core together with the CO_2 record from Byrd Station [*Neftel et al.*, 1988; *Staffelbach et al.*, 1991]. The common time scale is as in Fig. 1b (see text). The dashed lines through the Byrd $\delta^{18}O$ and the Vostok δD data are polynominal fits to better show the tendencies. Crosses denote CO_2 measurements on Byrd. The solid line in the CO_2 record connects the mean values for each depth level. Error bars are standard deviations for the mean values of one depth level. The dotted line is a linear fit over the age range 13.5-11.5 kyr BP. The approximate position of the Antarctic Cold Reversal [*Jouzel et al.*, 1995] and the Younger Dryas position defined by the prominent drop in the CH_4 concentration in the GRIP ice core are indicated by shaded areas.

at 14.5 kyr BP is 400-1500 yr. However, only the minimal shift of 400 yr leads to results which are still in agreement with the independent Byrd time scale [*Hammer et al.*, 1994]. This small correction of the Byrd relative to the GRIP time scale is also within the uncertainty of the dating by $\delta^{18}O_{air}$ [*Sowers and Bender*, 1995]. The adjustment of the Byrd and the Vostok time scale leads to synchronous isotope-temperature signals. This is in agreement with the Byrd/Vostok time scale fitting with dust profiles [*Jouzel et al.*, 1995]. The relative shift of the time scales is restricted to the investigated time interval and should be extrapolated neither to younger nor older times.

Our results confirm, that the ACR precedes the YD event. The interrupt of the Antarctic temperature increase starts at least 1.8 kyr before the drastic YD cooling. The ACR corresponds to a period of cooling in Greenland. Throughout the YD the Antarctic temperature is increasing, starting about 1 kyr before the YD/Preboreal transition. Antarctica reaches its Holocene temperature already at the end of the YD while in Greenland the abrupt temperature increase is followed by a slower increase for at least another 1.5 kyr.

The common time scale between the three ice cores allows us now to compare the evolution of the CO_2 signal and that of $\delta^{18}O$ from Summit. The following discussion is based on the detailed Byrd CO_2 record [*Neftel et al.*, 1988; *Staffelbach et al.*, 1991]. The Vostok record includes only 6 measurements from 16 to 10 kyr BP [*Barnola et al.*, 1991] which are in good agreement with the Byrd results. The abrupt YD cooling in the North Atlantic region is not reflected in the CO_2 record which exhibits a nearly linear increase from 245 to 265 ppmv during that period, invalidating the CO_2 variations seen in measurements from stomatal density of fossil leaves [*Beerling et al.*, 1995]. Current climate models simulating this event suggest that the North Atlantic deep water formation was strongly reduced and sea surface temperature has cooled by about $\geq 6°C$ [*Schiller et al.*, 1997; *Stocker and Wright*, 1996]. This tends to decrease the atmospheric CO_2 concentration due to increased solubility and due to a better utilisation of nutrients because of the longer residence time of the surface waters in the North Atlantic [*Keir*, 1988; *Wenk and Siegenthaler*, 1985]. However, our data indicate that changes in the surface conditions of the ocean or in the marine carbon cycle in regions other than the North Atlantic must have compensated these effects. An active thermohaline circulation in the North Atlantic tends to cool the southern hemisphere [*Crowley*, 1992]. Hence, there was most likely a large-scale warming of the southern hemisphere ocean surface during YD of about 1°C as recent model simulations suggest [*Schiller et al.*, 1997; *Stocker and Wright*, 1996]. Such an out-of-phase relationship between northern and southern hemispheres during YD is consistent with the ACR preceding YD by about 1.8 kyr and with a general warming during YD suggested by the isotopic records in Antarctica [*Broecker*, 1997]. Reconstructions of sea surface temperature based on marine sediment cores from the southern ocean further support this finding: temperature increased rapidly in the south in synchrony with the YD cooling in the north [*Labracherie et al.*, 1989]. Our data show that the net influence of the YD abrupt cooling on the atmospheric CO_2 concentration is only minor. Based on this and the fact that the glacial-interglacial CO_2 increase starts before the temperature increase in Greenland [*Anklin et al.*, 1997] we conclude that the atmospheric CO_2 concentration is not dominated by changes in the North Atlantic Deep Water formation during YD.

In summary, the synchronisation of Greenland and Antarctic ice cores by CH_4 leads to the following improvements: 1) the ACR leads the YD by at least 1.8 kyr; 2) CO_2, measured on the air included in the Byrd ice core, rose steadily during the YD disproving changes seen in a CO_2-proxy record [*Beerling et al.*, 1995]; 3) the net North Atlantic influence on the atmospheric CO_2 concentration is small during YD.

Warm stages of 1-3 kyr (Dansgaard-Oeschger events) were observed in the temperature record of central Greenland during the LG. These events as well as the YD parallel changes in the surface temperature in the North Atlantic [*Bond and Lotti*, 1995] and are associated with significant changes in the world ocean circulation. Since the North Atlantic seems to have only a minor influence on the CO_2 concentration during YD we expect only minor changes during Dansgaard-Oeschger events. This is confirmed by the CO_2 results from the Byrd core which show variability of <20 ppmv in the glacial [*Neftel et al.*, 1988; *Staffelbach et al.*, 1991].

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