A novel method to study the phase relationship between Antarctic and Greenland climate

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[1] A classical method for understanding the coupling between northern and southern hemispheres during millennial-scale climate events is based on the correlation between Greenland and Antarctic ice core records of atmospheric composition. Here we present a new approach based on the use of a single Antarctic ice core in which measurements of methane concentration and inert gas isotopes place constraints on the timing of a rapid climate change in the North and of its Antarctic counterpart. We applied it to the Marine Isotope Stage (MIS) 5d/c transition early in the last glaciation ~108 ky BP. Our results indicate that the Antarctic temperature increase occurred 2 ky before the methane increase, which is used as a time marker of the warming in the Northern Hemisphere. This result is in agreement with the "bipolar seesaw" mechanism used to explain the phase relationships documented between 23 and 90 ky BP [*Blunier and Brook*, 2001]. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4267 Oceanography: General: Paleoceanography; 1827 Hydrology: Glaciology (1863); 4870 Oceanography: Biological and Chemical: Stable isotopes; 1620 Global Change: Climate dynamics (3309). **Citation:** Caillon, N., J. Jouzel, J. P. Severinghaus, J. Chappellaz, and T. Blunier, A novel method to study the phase relationship between Antarctic and Greenland climate, *Geophys. Res. Lett.*, *30*(17), 1899, doi:10.1029/2003GL017838, 2003.

1. Introduction

[2] Comparison of records obtained from ice cores drilled in both polar ice sheets can show whether Greenland temperature variations on millennial time scales have their counterpart in Antarctica, and if those changes are or are not synchronous. The Greenland ice $\delta^{18}O$ record revealed 24 interstadials (warm intervals referred to as Dansgaard/Oeschger or D/O events) of less than 3 ky duration during the last glacial period [*Dansgaard et al.*, 1993]. These events are characterized by an abrupt warming of as much as 10°C within decades [*Lang et al.*, 1999; *Severinghaus et al.*, 1998, 1999] followed by a gradual (centuries-long) cooling. The intensity of the North Atlantic thermohaline circulation is considered to be one of the key elements associated with those abrupt events [*Broecker and Denton*, 1989; *Dansgaard et al.*, 1984], although alternative hypotheses involving tropical mechanisms have been proposed [*Clement et al.*, 2001].

[3] Although Antarctic temperature variations retrieved from δD or $\delta^{18}O$ of ice show a different pattern with less pronounced changes [*Johnsen et al.*, 1972; *Jouzel et al.*, 1987], it is now clear that millennial scale variability is also imprinted in the Antarctic temperature record [*Bender et al.*, 1999; *Blunier et al.*, 1998, 2001].

[4] What is the succession of climate events between hemispheres on millennial time scales during the last glacial period? This question can be addressed by synchronizing gas records from air entrapped in ice from Antarctica and Greenland. This method, extensively applied for the last deglaciation and part of the last glacial period, requires a correct estimate of the age difference between ice and the entrapped gas (Δ_{age}) in order to compare the climate signal recorded in the gas (CH_4) with that in the ice (temperature). Δ_{age} can be estimated using a firn densification model (i.e., *Barnola et al.* [1991]). However, for low accumulation sites such as Vostok (Antarctica), the uncertainty on Δ_{age} can be up to 1 ky during a glacial period [*Petit et al.*, 1999], which severely limits the accuracy of inter-hemispheric synchronization. *Bender et al.* [1999, 1994] first used this approach to place the GISP2 (Greenland) and Vostok cores on a common time scale by using the isotopic composition of atmospheric oxygen. They concluded that the D/O events found at GISP2 between 35 and 75 ky BP also occurred at Vostok and that corresponding events are on average in phase within ±1.3 ky [*Bender et al.*, 1999]. *Blunier and Brook* [2001] followed a similar approach but used atmospheric methane concentration records. Because methane is rapidly mixed in the atmosphere compared with its residence time (~10 yr), its variations can be very rapid and still be imprinted almost simultaneously in both hemispheres. Based on a comparison between Byrd (Antarctica) and GISP2 and GRIP records, they showed that the onset of millennial-scale warmings in Antarctica preceded the onset of warmings in Greenland by 1.5 to 3 ky over the period from 90 to 23 ky BP. Indeed, the apparent contradiction between *Blunier and Brook* [2001] and *Bender et al.* [1999] is a matter of definition (simply due to the different shape of Greenland and Antarctic events). As noted in *Blunier and Brook* [2001], a comparison of peak temperatures as done in *Bender et al.* [1999] would also lead to the conclusion that Byrd and GRIP/GISP2 events are in phase.

[5] There is a major problem if we want to extend the synchronization between Greenland and Antarctica further back in time, for the period corresponding to the early part of the last glacial period. Disturbances that take place in the

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bottom part of GRIP and GISP2 ice cores [*Chappellaz et al.*, 1997; *Grootes et al.*, 1993], make it difficult to get an accurate timescale and thus to correctly estimate Δ_{age} for those cores. To overcome those difficulties we propose an approach based on the interpretation of Vostok records only, which continue undisturbed back to 400 ky BP. Moreover, we only use parameters which are measured in air bubbles, avoiding the large uncertainty associated with Δ_{age} at this site. We focus on the transition around 108 ky BP, anticipated to correspond to D/O 24. We first illustrate the difficulty of correlating GRIP and Vostok using CH_4 records measured at those sites despite the very detailed new measurements we have obtained, and then show how this difficulty can be circumvented using Vostok records only.

2. Correlation Using Vostok and GRIP CH_4 Records

[6] The CH_4 records published for Vostok [*Chappellaz et al.*, 1990] and GRIP [*Chappellaz et al.*, 1997] have too coarse a resolution for the early glacial to undertake a synchronization of those two cores. We thus performed for both sites new CH_4 measurements with a high temporal resolution (better than 100 years). These new data sets are shown in Figure 2, for which we have kept the published GRIP and Vostok timescales, simply adjusting and scaling them in order to get the best possible visual correlation of the CH_4 records. The rapid CH_4 increase from 450 to 600 ppvb corresponding (nominally) to the start of the MIS 5d/c transition (hereafter 5d/c) is well marked in Vostok CH_4 at the depth of 1533 m (105.5 ky BP) and in GRIP at 2758 m (105 ky BP). There is thus a good correspondence between the Vostok and GRIP ages of this increase. This is not surprising because the depth corresponding to MIS 5d has been chosen as a time-marker at both sites [*Dansgaard et al.*, 1993; *Jouzel et al.*, 1987] with an assigned age of 110 ky BP. However, there is no good correspondence between the two timescales over the entire interval shown on Figure 2, with the duration of the CH_4 peak being more than twice longer at GRIP than at Vostok. We attribute this large difference to the ice flow disturbances associated with the proximity of the bedrock [*Chappellaz et al.*, 1997], leading to variable annual layer thicknesses in this depth range. This bad correlation above 106 ky BP might also result from an underestimation of the GRIP accumulation rate during MIS 4, as recently pointed out by *Wagner et al.* [2001]. In turn, uncertainties on accumulation rate and possible ice flow disturbances around the 5d/c at GRIP imply that calculated Δ_{age} would be highly uncertain. This together with the large Vostok Δ_{age} uncertainty clearly prevents a correlation of the GRIP and Vostok climate records that is sufficiently precise to evaluate inter-hemispheric phase lags, even when very detailed CH_4 records are available. However, these detailed methane data provide a new constraint on the GRIP dating, which will help to get a correct GRIP gas timescale even in this part of the record where the chronology of the ice itself is uncertain.

3. Correlation Using Parameters Measured in the Vostok Air Bubbles

[7] *Caillon et al.* [2001] have shown that detectable anomalies in nitrogen and argon isotopes are associated with the 5d/c at Vostok. Detailed $\delta^{15}N$ and $\delta^{40}Ar$ data allowed them to identify the start of this transition. Here we combine those data with the CH_4 profile, which is assumed to reflect climatic changes in the tropics and northern hemisphere [*Brook et al.*, 2000; *Chappellaz et al.*, 1993; *Dällenbach et al.*, 2000]. Indeed, previous studies indicate that increases in methane concentration occurred nearly synchronously (within 30 yr) with the onset of rapid warming events in the GISP2 and GRIP stable isotope records during glacial period, when tropical wetlands have been proposed as a major sources of methane [*Brook et al.*, 2000, and references herein].

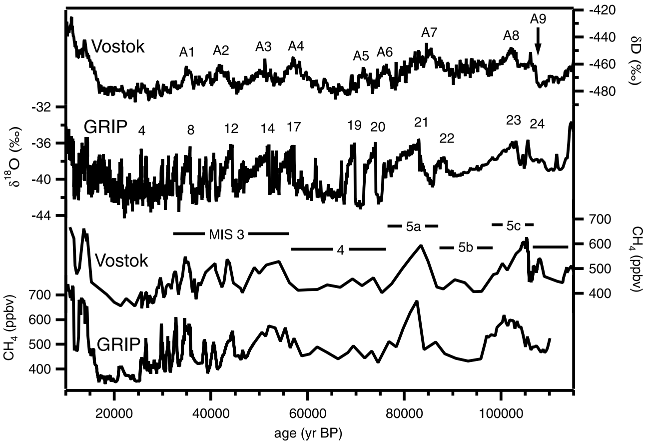

Figure 1. Vostok and GRIP water-isotope profiles versus age [*Dansgaard et al.*, 1993; *Jouzel et al.*, 1987] and CH_4 records combining new data with that obtained by [*Chappellaz et al.*, 1990] for Vostok and by *Blunier et al.* [1998] for GRIP (age given by *Petit et al.* [1999] for δD profile of Vostok and *Johnsen et al.* [1995] for $\delta^{18}O$ profile of GRIP). The arrow shows the position of the rapid step-up in water isotopes that is interpreted as the 5d/c. Interstadial events are numbered, and approximate locations of marine isotope stages are shown.

[8] The trapped air bubbles in ice contain a sample of the atmosphere with a composition slightly modified by gravitational settling and thermal diffusion in the firn layer on top of the ice sheet [*Schwander*, 1989; *Severinghaus et al.*, 1998]. The isotopic signals, which are preserved in the bubbles as the air is trapped in the ice, appear to be related to temperature change at the surface [*Caillon et al.*, 2001, 2003; *Lang et al.*, 1999; *Leuenberger et al.*, 1999; *Severinghaus et al.*, 1998, 1999]. *Caillon et al.* [2001] have focused on the 5d/c to estimate the temperature prior to the warming event using the $\delta^{40}Ar$ and $\delta^{15}N$ signals recorded in the gas phase. Deuterium, $\delta^{40}Ar$, $\delta^{15}N$ and CH_4 are plotted in Figure 3. In the $\delta^{40}Ar$ and $\delta^{15}N$ profile a step-like decrease around 1567 m is interpreted as the result of the temperature change that occurred at the surface of the ice cap. Rapid warming should cause a reduction of the gravitational effect due to the thinning of the firn, which is the expected consequence of more rapid firn densification at warmer temperature (see *Caillon et al.* [2001] for details). Note that *Caillon et al.* [2003] published a set of $\delta^{40}Ar$ performed on the Vostok core that showed higher $\delta^{40}Ar$ values during interglacial than during glacial time. That behavior ($\delta^{40}Ar$ and temperature positively correlated) is opposite to the inferred behavior of

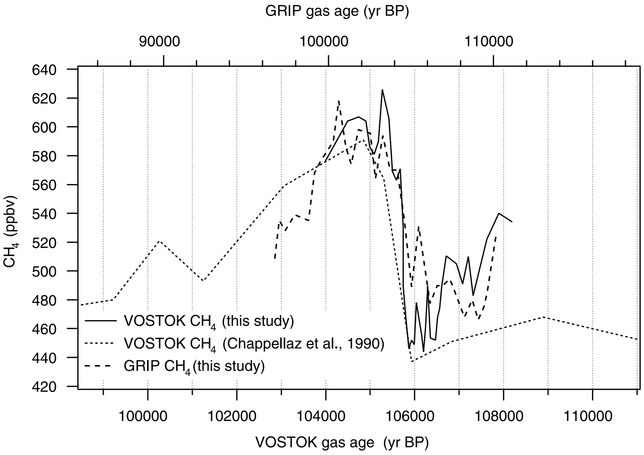

Figure 2. Detailed measurements of CH_4 concentration for the 5d/c in Vostok ice and in GRIP ice with respect to age. The GRIP scale has been shifted in order to obtain the best correlation between GRIP and Vostok signals.

the firn reported by *Caillon et al.* [2001]. Further studies are necessary to decipher the puzzling differences between the processes involved in both cases.

[9] We then compare the isotopic records with the abrupt methane increase recorded at 1533 m. According to the Vostok dating [*Petit et al.*, 1999], the depth difference between the CH_4 increase and $\delta^{40}Ar$ and $\delta^{15}N$ decreases represents an age difference of 2 ky. We assume that temperature and methane changes are coeval in the Greenland ice. It implies that this Antarctic warming significantly preceded the rapid change in Greenland at the start of the last glacial period.

4. Discussion and Conclusions

[10] Results presented here allow us to suggest the following sequence of events: (1) the Antarctic warming corresponding to the 5d/c occurred when Greenland was still cooling down (the methane was still decreasing when $\delta^{15}N$ and $\delta^{40}Ar$ decreased at 1565 m), and (2) the abrupt temperature increase corresponding to D/O 24 observed in Greenland ice took place 2 ky after the one observed in Vostok. In keeping with the pattern identified by *Blunier and Brook* [2001] for younger events, Greenland remained cold while the Antarctic temperature increased. A weakness of our method is that it places timing constraints only on the initiation of the Vostok warming trend. Therefore it is difficult to conclude that the end of the cooling in Greenland, coincides with a cooling or a reversal situation in Vostok. However, we can estimate the overall duration of warming in the ice deuterium record from the Vostok dating with an accuracy of probably better than ±10% [*Petit et al.*, 1999]. Its duration is slightly less than 2 ky, which would indicate a slight lag of the Greenland peak temperature with respect to the Antarctic one. Given the complex shape of the Vostok MIS 5c deuterium curve, however, it is unclear if the sequence of events at that time can be directly compared to the large Antarctic events that *Blunier and Brook* [2001] have numbered A1 to A7 (following this description the event starting at 108 ky BP would be A9 with A8 corresponding to the broad event peaking at 103 ky BP).

[11] The sequence of events between Antarctica and Greenland that we found is consistent with the bipolar seesaw mechanism [*Broecker*, 1998; *Stocker*, 1998] in which the south Atlantic warms in response to the thermohaline circulation collapse in the North Atlantic and its associated effect on the inter-hemispheric heat transport.

[12] *Blunier and Brook* [2001] concluded that warming on millennial time scales in Antarctica preceded the onset of Greenland warming by 1.5 to 3 ky due to the operation of a bipolar seesaw in air temperatures and an oceanic teleconnection between hemispheres. However, despite the consistent association of climatic variability with abrupt changes in thermohaline circulation in the north hemisphere [*Bond et al.*, 1993], a causal role for the thermohaline instability has not yet been established and the ultimate forcing behind this climatic seesaw remains unclear. We caution against inferring causation from lead-lag relationships. The succession of events in the hemispheres cannot be considered diagnostic of the location of origin of millennial-scale climate changes, nor of the physical mechanisms involved [*Johnsen and Stocker*, 2003; *Steig and Alley*, 2001].

[13] Our estimate is in good agreement with that obtained by *Blunier and Brook* [2001]. However, we note that the magnitude of time differences between Antarctica and Greenland warmings may differ for the large D/O events, as examined both in *Blunier and Brook* [2001] and in this study, and the small intervening Antarctic counterparts of D/O events. Such a different behavior has been suggested recently by *Raisbeck et al.* [2002] at the time of the small event associated with D/O 10, using high-resolution ^{10}Be

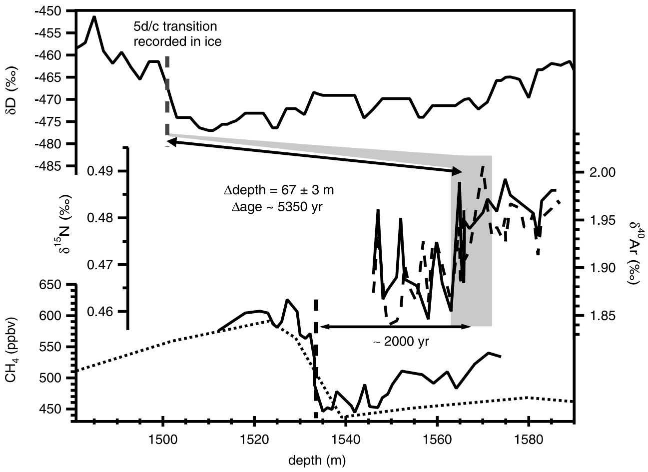

Figure 3. δD [*Jouzel et al.*, 1987]; $\delta^{40}Ar$ (plain) and $\delta^{15}N$ (dash) [*Caillon et al.*, 2001] and CH_4, versus depth in the Vostok ice core. Firn densification models in combination with the Vostok timescale [*Petit et al.*, 1999] predict a Δ_{age} of ~5 ky in this interval. This corresponds to a depth difference (Δ_{depth}) of 63 m, with an estimated uncertainty of 20%, implying that the gas isotope signal should lie between 1577 and 1553 m. The depth interval covered by the gas isotope data is large enough that the gas trapped during the warming should fall within this interval (1546–1587 m).

profiles from GRIP and Dome C (Antarctica) for interpolar synchronization. This suggests that we face a complex situation as far as the timing of millennial scale Greenland and Antarctic events is concerned. Acquiring new information is thus useful, and, although its application should be limited to large events, the novel approach we have developed in this study is promising. As it is based on records from one single Antarctic core, it has the potential to shed light on the timing of Antarctic and Greenland climates over 4 climatic cycles at Vostok, or even more at Dome C, far beyond the period over which the Greenland record is available, providing constraints that allow discussion of the temporal and global extent of asynchronous millennial-scale variability.

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