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A new 27 ky high resolution East Antarctic climate record

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Abstract. The ice core recently drilled at the Dome Concordia site on the East Antarctic plateau provides a new high resolution isotope record covering part of the last glacial, the last transition and the Holocene. The two step shape of the deglaciation is remarkably similar for all the ice cores now available on the East Antarctic plateau. The first warming trend ends about 14000 years ago and is followed by the well marked Antarctic Cold Reversal (ACR) with a secondary peak common to all records. During the deglaciation, there are more similarities between the near coastal site of Taylor Dome and inland East Antarctica than between Taylor Dome and central Greenland. However, the results for EPICA do appear to confirm the Taylor Dome timescale after about 14 ka, showing cooling into the ACR roughly in phase between Greenland and Antarctica. While the overall deglacial pattern is asynchronous, this suggests that the now classical picture of a temperature seesaw between Antarctica and Greenland may be too simplistic.

1. Introduction

Whereas numerous deep-sea, continental and ice core records covering the last deglaciation are now available [*e.g. Alley and Clark, 1999*], the driving mechanisms of this climatic transition are still not fully understood. Recent studies highlight the central role of the huge unstable Northern Hemisphere ice caps and their interaction with the oceanic thermohaline circulation in the North Atlantic. They also reveal that the Antarctic deglacial warming started before the sharp Greenland warming marking the onset of the Bölling and was interrupted by the so-called Antarctic Cold Reversal [hereafter ACR ; *Jouzel et al., 1995*].

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Our knowledge of the timing of the deglaciation has recently benefited from the interpretation of ice core isotopic profiles (δD or $\delta^{18}O$, which are proxies of temperature change) from both hemispheres. Those cores can now be cross dated owing to the global synchronism of air composition changes [*Sowers and Bender, 1995 ; Blunier et al., 1998*]. Still, as far as Antarctica is concerned, conclusions are mainly based on two records only, Byrd in West Antarctica and Vostok in Central East Antarctica (Figure 1). However, none of them is ideally suited for this purpose. The Byrd isotopic temperature record may significantly be affected by changes in the altitude of the ice cap and in the origin of the ice flow [*Raynaud et al., 1982*]. The Vostok chronology is poorly constrained with respect to Greenland records because of the large uncertainty associated with the gas age-ice age difference in this low accumulation site. As a result it is difficult to precisely answer questions about the initial start of the deglaciation in Antarctica and about the comparison of its shape and timing between East and West Antarctica or between East Antarctica and Greenland. To answer such questions there is a need to obtain more isotopic records with the best possible resolution at various places in Antarctica. This need is strengthened by the data recently obtained from the Taylor Dome core (hereafter TD), which on the published timescale appears to indicate synchronous climatic changes between this Ross Sea sector of Antarctica and the North Atlantic [*Steig et al., 1998*].

We present here a new δD profile measured along an ice core recently drilled at Dome Concordia, a site located on the Central East Antarctic Plateau (CEAP) in between TD and more inland ice drilling sites such as Vostok (Figure 1). The interest of this new record recovered in the frame of the European Project for Ice Coring in Antarctica (hereafter EPICA DC) lies in its excellent temporal resolution (typically 20 years in the Holocene and 50 years in last glacial). Also Vostok receives a significant amount of moisture from the Atlantic and TD is dominantly influenced by the Pacific ; in contrast, the Dome Concordia site should receive most of its moisture from the Indian ocean [*Delaygue et al., 2000a, Werner et al., 2001*]. In addition to EPICA Dome C, we discuss a new detailed and continuous record of the bottom part of the inland core drilled at Komsomolskaia (Figure 1) up to now documented at very coarse resolution [*Ciais et al., 1992*].

2. The EPICA Dome C Deuterium Record

Topographic and radar measurements carried out in the DC region [*Tabacco et al., 1998*] allowed the determination of the EPICA drilling site on the topographic dome centered at 75°06'06"S, 123°23'42"E at an elevation of 3233m. The ice thickness is of 3250 ± 25 m and the mean annual air temperature is -51.1°C. The EPICA site is located 50 km SSW of the site where a 906 m thermal core (hereafter old Dome C) was drilled during the 1977-1978 field season [*Lorius et al., 1979*]. The EPICA DC core has been recovered by the means of an electro-mechanic drilling in two seasons 1997-1998 and 1998-1999 but

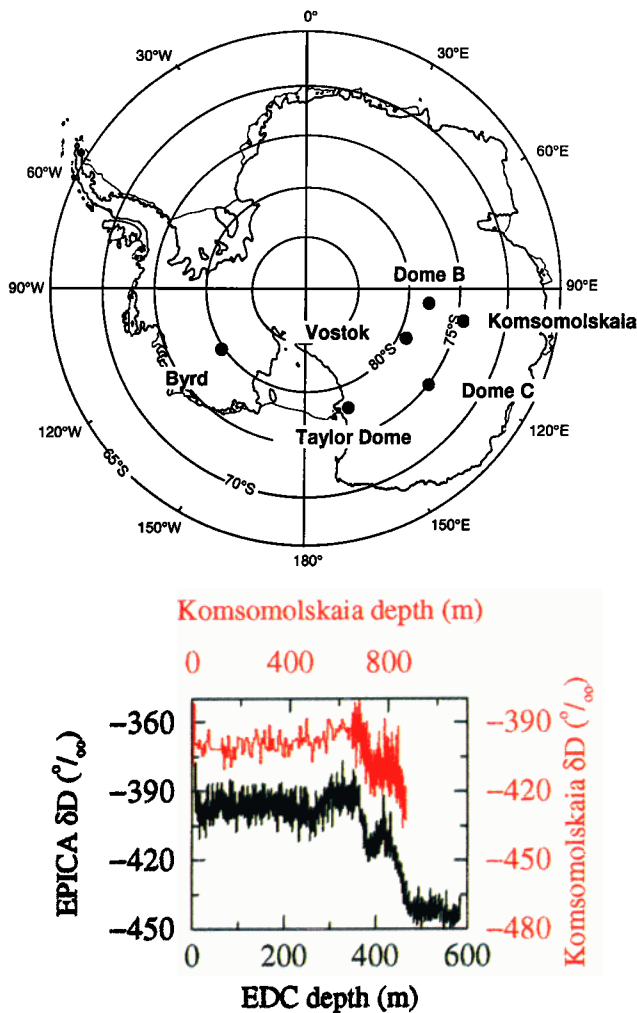


Figure 1. Map of Antarctica showing the location of Antarctic drilling sites along with the EPICA Dome C δD record with respect to depth. We have in addition reported the deglaciation part of the Komsomolskaia core over which detailed measurements have been performed.

the drill was unfortunately stuck at the end of the second season. This core was sampled at a 55 cm length and the first 585 m were analyzed for δD with a precision of $\pm 0.5\%$ [Vaughn et al., 1998].

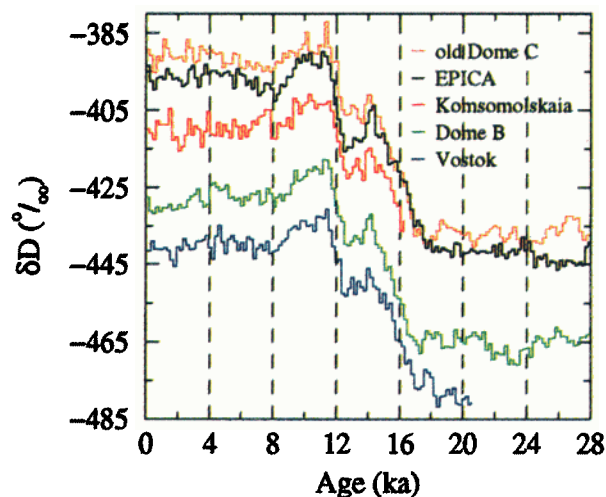


Figure 2. Comparison of deglaciation δD profiles from 5 different sites located on the East Antarctic plateau at 200 year resolution.

A chronology of the EPICA DC core (EDC1) has been established combining a modeling approach, the use of time markers and comparison with other records [Schwander et al., in press]. It uses two reference ages: (1) the end of the Younger Dryas 11.5 ka (thousands of years before present) derived from isotope match with Byrd, and (2) the ^{10}Be peak discovered in the old Dome C and Vostok cores [Raisbeck et al., 1987] supposed to result from the Laschamps geomagnetic excursion (~ 41 ka). It also benefits from a correlation with the Byrd core through a common fluoride peak observed at 17.3 ka and additional volcanic events.

The δD measurements show lightest isotopic values in EPICA DC than in old DC [Jouzel et al., 1982] with a constant offset of about 5‰. This shift may be explained by local meteorological conditions, since EPICA DC has a much colder winter surface temperature (by 1.3°C) and a 15% lower accumulation than old DC (2.7 and $3.4 \text{ g}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$).

The temperature interpretation based on the use of the present-day spatial isotope/temperature slope as a surrogate of the temporal slope clearly underestimates temperature changes in Greenland [Cuffey et al., 1995; Johnsen et al., 1995], likely due to changes in precipitation seasonality [Krinner et al., 1997; Werner et al., 2000]. Model results suggest that seasonality has less influence on Antarctic precipitation [Krinner et al., 1997; Delaygue et al., 2000b]. In the absence of strong argument against it, this classical temperature interpretation is still considered as valid for Antarctic isotopic profiles [Petit et al., 1999]. Other factors such as changes in the origin of the precipitation, in the cloud microphysics or in the strength of the inversion should influence the isotopic content of polar snow.

Stenni et al [submitted] have used the EPICA DC deuterium-excess parameter ($d = \delta D - 8\delta^{18}\text{O}$), largely governed by the moisture source temperature, to confirm that δD changes mainly depend on the temperature of the site with a dependency to surface temperature close to that observed for present-day surface snow in this sector. They infer a glacial to Holocene optimum surface temperature change of 9°C , taking into account the glacial-interglacial change in the oceanic source regions as inferred from the deuterium-excess record and in the isotopic composition of the ocean.

3. Comparison with Other Isotopic Ice Core Records

Figure 2 displays the δD records available on ice cores from Central East Antarctica with from top to bottom, old and EPICA DC, Komsomolskaia, Dome B and Vostok. For Vostok, we use the 4 Γ profile [Jouzel et al., 1992] which is more detailed than the 3 Γ one. The Komsomolskaia profile includes new data in its deglaciation part now measured on a continuous and detailed basis (Figure 1). We use the published timescales for Dome B [Jouzel et al., 1995], Komsomolskaia [Ciais et al., 1992] and Vostok [GT4 timescale of Petit et al., 1999]. Figure 2 shows an excellent agreement between the δD profiles of EPICA DC, Komsomolskaia, Dome B and Vostok without any timescale adjustment. In particular, deglaciation is synchronous for these 4 inland sites which is corroborated by available dust profiles [Mulvaney et al., 2000] and by precise depth correlation between Vostok and EPICA DC based on a matching of major peaks of electrical conductivity [Wolff et al., 1999]. Instead, the old Dome C timescale [Jouzel et al., 1982] is 4% younger than EPICA DC at mid-deglaciation and has been linearly adjusted in Figure 2.

The 5 CEAP records show a similar two-step deglaciation pattern, starting at about 18 ka with a first warming trend ending at ~ 14 ka as proposed by Jouzel et al. [1995]. This dating thus places this well marked event younger (up to 1000 years) than the

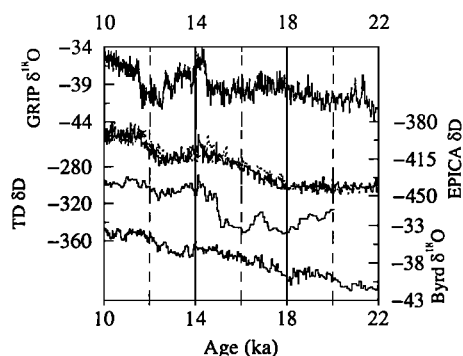


Figure 3. EPICA DC record compared to records of the transition in near-Coastal East Antarctica (Taylor Dome), West Antarctica (Byrd) and central Greenland (GRIP). In addition to the EPICA DC record obtained using the EDC1 glaciological timescale (continuous line) we have reported this record (dotted line) as dated by direct correlation with the GRIP SSO9 timescale (Schwander et al., in press).

Vostok chronologies derived by correlation with the Greenland records using either atmospheric oxygen 18 [Sowers et al., 1992] or methane data [Blunier et al., 1998]. Note that such a correlation performed between EPICA DC and GRIP using CH_4 records, provides ages older than EDC1 [Schwander et al., in press]. The 400 years difference observed around 14 ka (see Figure 3) is however well within the uncertainty associated with the ice age–gas age difference.

The first warming (35‰ δD) is followed by a relatively abrupt cooling (10‰ δD) already documented as the onset of the ACR [Jouzel et al., 1992 ; 1995], with its coldest part between ~ 13.5 and 12.5 ka then followed by a second warming step (25‰ δD) reaching the so-called Holocene optimum at about 11.5 ka. The amplitude of the isotopic changes is remarkably common to all the different ice cores, independently of their geographic spreading and of the absolute level of modern δD content of surface snow. The internal shape of the ACR is remarkably consistent between the 5 records with a secondary maximum particularly well marked in our two new records of the last deglaciation, EPICA DC and Komsomolskaia.

Figure 3 compares the EPICA DC deglaciation record that we will take as a reference for CEAP with those of Byrd (West Antarctica), TD (near coastal site in the Ross Sea sector of East Antarctica) and GRIP (central Greenland). The deglacial warming started first in Central Greenland (where the coldest period was around 25 ka) and then at ~ 18 ka both in West Antarctica (Bender et al., 1999) and in central East Antarctica (note however low values at Byrd around 22 ka). Steig et al. [1998] indicated that this warming started even later at TD and was abrupt around 15 ka. However, aerosol results suggest that TD and EPICA DC climate changes may be synchronous for this first part of the deglaciation [Mulvaney et al., 2000]. As pointed out by Jouzel et al. [1995], the shape of the deglacial warming then differs between East and West Antarctica with the ACR being well marked in East Antarctica (and very consistently in the 5 CEAP records) and less pronounced and shorter at Byrd. This first warming ends around 14 ka at all Antarctic sites ~ 500 years later than the onset of the Bolling Allerod in Greenland (however, the CH_4 correlation with GRIP makes those two events coeval, drawing attention on the difficulty of precisely comparing Greenland records with those of CEAP). Unlike shown in Steig et al. [1998], the climate records of central and near coastal East

Antarctica are relatively similar after 14 ka with however a slightly less pronounced cooling at TD (again within dating uncertainty). Steig et al. [1998] used an old timescale for the Vostok core which caused them to incorrectly conclude that both Byrd and Vostok cooled earlier than TD. However, their conclusion that the Byrd cooling appears earlier than at TD or elsewhere in East Antarctica appears to be correct. Moreover, the similarity now observed for the second part of the deglaciation between CEAP cores and TD, strongly suggests that the TD dating is correct for ages younger than ~ 14 ka. Overall, the interpretation of EPICA DC data supports the picture that in East Antarctica, including TD, the last deglaciation is characterized by a long gradual warming interrupted by the ACR. The two warming periods started in Antarctica before the abrupt transitions in Greenland, leading the onset of the Bölling Allerod and the end of the Younger dryas by ~ 3.5 and 1 ka respectively. On the other hand, the cooling period occurring after the first warming appears roughly in phase at the two poles.

Unlike for the deglaciation, the 5 CEAP records exhibit significantly different isotopic trends during the Holocene (Figure 2). EPICA and old DC records show a sharp isotopic decrease ending the early Holocene optimum and leading to the weakest isotopic values of the Holocene around 8 ka. This is followed by an increasing trend until 4.5 ka and stable values afterwards. Instead, Vostok, Dome B and Komsomolskaia all located further East and inland reflect a δD decreasing trend all over the Holocene with varying slopes. As pointed out by Masson et al. [2000], such different isotopic trends may reflect relative changes in the topography of the East Antarctic ice sheet at these different locations in response to the accumulation increase due to warmer temperatures. Such variations would be consistent with relative changes in ice sheet topography of 15 m/ka between Dome Concordia and Vostok between 8 ka and nowadays. Superimposed on the long term Holocene trend, the EPICA DC δD record shows some organised variability in common with old DC (warm rapid events with an amplitude reaching typically 5‰ can be identified ~ 1.4 , 2.8, 3.8 to 6 and 7.7 ka).

4. Conclusion

The two step shape of the last deglaciation in East Antarctica was first noted in the old DC isotopic record, from where the ACR was originally defined, and then characterized in the Vostok and Dome B records. This event is now fully depicted in two new records EPICA DC and Komsomolskaia and the duration, amplitude and internal shape of the ACR showing a well marked secondary maximum, are remarkably similar in those 5 CEAP cores. Such similarities apply for the last deglaciation as a whole but Holocene trends slightly differ between the Dome Concordia and Vostok sites likely due to changes in ice sheet topography.

The EPICA DC chronology established by Schwander et al. [in press] indicates that the deglaciation started at ~ 18 ka with a first warming trend ending at ~ 14 ka almost synchronously in all Antarctic sites. There is then a different behavior with the ACR cooling lasting shorter and being less pronounced at Byrd than over the CEAP region. However, the possible influence of changes in altitude and in the origin of the ice on the Byrd record as well as dating uncertainties should be kept in mind. Between 14 and 11 ka TD and CEAP records may be relatively similar as previously suggested by Mulvaney et al. [2000] for the earlier part of the deglaciation. Overall, the EPICA DC results definitely

question that the Ross Sea sector of East Antarctica experienced a particularly strong "North Atlantic" signal.

The picture that now emerges is that all East Antarctic cores, including TD, have a similar deglaciation history characterized by a long gradual warming interrupted, between ~14 and 12.5 ka, by the ACR. The two periods of warming lead the abrupt transitions in Greenland. Instead the cooling after 14 ka is roughly in phase between Greenland and Antarctica. This gives a deglaciation pattern (asynchrony) quite parallel to that observed during the A1 and A2 glacial events in Antarctica and the corresponding Dansgaard-Oeschger events in Greenland [Blunier *et al.*, 1998]. In turn, the now classical picture of a seesaw [Broecker 1998; Stocker, 1998] between Antarctica and Greenland during the last deglaciation, i.e. Greenland warms when Antarctica cools and conversely, may be too simplistic. However, our results are in agreement with present modeling efforts [Ganapolski and Ramstorf, 2001] based on changes in the inter-hemispheric heat transport induced by variations of the Atlantic thermohaline circulation.

Finally, it should be noted that the region covered by our 5 East Antarctic records only represents about one third of East Antarctica. Obtaining new records at coastal sites such as Law Dome or inland such as at Dome Fuji (where an event similar to the ACR is clearly seen but not yet crossdated with other records) and at the EPICA Dronning Maud Land site in East Antarctica or at SIPLE Dome in West Antarctica, are highly desirable.

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