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A late-glacial high-resolution site and source temperature record derived from the EPICA Dome C isotope records (East Antarctica)

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Abstract

The timing and synchronisation of Greenland and Antarctic climate events that occurred during the last glacial period are still under debate, as is the magnitude of temperature change associated with these events. Here we present detailed records of local and moisture-source temperature changes spanning the period 27–45 kyr BP from water stable isotope measurements (δD and $\delta^{18}O$) in the recently drilled EPICA Dome C ice core, East Antarctic plateau. Using a simple isotopic model, site (ΔT_{site}) and source (ΔT_{source}) temperatures are extracted from the initial 50-yr high-resolution isotopic records, taking into account the changes in seawater isotopic composition. The deuterium isotope variability is very similar to the less precise δD record from the Vostok ice core, and the site temperature inversion leads to a temperature profile similar to the classical palaeothermometry method, due to compensations between source and ocean water corrections. The reconstructed ΔT_{site} and ΔT_{source} profiles show different trends during the glacial: the former shows a decreasing trend from the warm A1 event (38 kyr BP) toward the Last Glacial Maximum, while the latter shows increasing values from 41 to 28 kyr BP. The low-frequency deuterium excess fluctuations are

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strongly influenced by obliquity fluctuations, controlling the low- to high-latitude temperature gradients, and show a remarkable similarity with a high-resolution southeast Atlantic sea surface temperature record. A comparison of the temperature profiles (site and source) and temperature gradient (ΔT_{source}-ΔT_{site}) with the non-sea-salt calcium and sodium records suggests a secondary influence of atmospheric transport changes on aerosol variations.

Keywords: deuterium excess; deuterium; ice cores; site temperature; source temperature; East Antarctica

1. Introduction

High-resolution palaeoclimatic records reveal a succession of rapid warmings and coolings (typically 10–15°C in a few decades) in and around the North Atlantic basin which have been attributed to severe changes in the ocean thermohaline circulation [1]. These millennial-scale climate changes seem to have had global counterparts. In Antarctica most of the large cooling episodes recorded in the North Atlantic region are characterised by warm events, while the termination of Antarctic warming coincided with the onset of rapid warming in Greenland, lending support to the concept of thermal anti-phasing between the hemispheres, or a 'bipolar see-saw' [2–6]. The large fluctuations in heat transport between the South and the North Atlantic, resulting from oceanic thermohaline circulation changes, may explain this behaviour [7]. An improved understanding of the timing and magnitude of temperature change in the two polar regions is required in order to evaluate the climate change mechanisms that were involved [8].

In this context, various scientific communities involved in palaeoclimatic research share a common interest in the time period spanning from ~20 to 50 kyr BP. For instance, this late glacial period has been the initial focus of studies dealing with the rapid changes documented in Central Greenland ice cores [9,10] and of their correlation with the Antarctic records [5]. The first correlation between the rapid climate changes recorded in ice cores [11,12] (the Dansgaard/Oeschger or D/O events) and in deep-sea cores (the Heinrich events) was also established for this time period [1]. This correlation enabled palaeoceanographers to propose amplifying mechanisms involving the interplay between ocean thermohaline circulation and ice sheet dynamics. The late glacial period is also of special interest because the time scale is relatively well-constrained. Radiocarbon dating can be applied back to ~45 kyr [13–15]. In addition, cosmogenic nuclide (e.g. ^{10}Be, ^{36}Cl) spikes associated with the Laschamp and other geomagnetic excursions permit synchronisation of the ice cores with both marine and terrestrial climate archives during the late glacial period [16–18]. In particular there is now the possibility of accurate dating based on U/Th measurements on speleothems [19,20]. Together these characteristics make studies of high-resolution climate records spanning the late glacial period of widespread interest.

In Antarctica (Fig. 1), several relatively low-resolution (centennial) climate records covering most of the late glacial period have been published. Deep ice cores have been recovered at Byrd [21], Dome C [22] (50 km from the EPICA Dome C site), Vostok [23], Dome B [24] and Taylor Dome [25]. Higher resolution was achieved in the recently published Dome F record which has decadal resolution over this period [26]. Climatic interpretation in all of these ice cores is based on either hydrogen (δD) or oxygen (δ^{18}O) isotopic ratios in the ice (H_2O). The two isotopic systems enable independent first-order estimates of temperature, at least in East Antarctica [27]. Ice from the late glacial is also available from Law Dome [28] and Siple Dome [29] but continuous isotopic profiles spanning the late glacial period are not yet published.

The deuterium excess profile, $d = \delta D - 8\delta^{18}O$, provides additional information on oceanic moisture sources and allows the deconvolution of the distal moisture source temperature and the local temperature at the site of precipitation. This approach has been applied over a variety of time

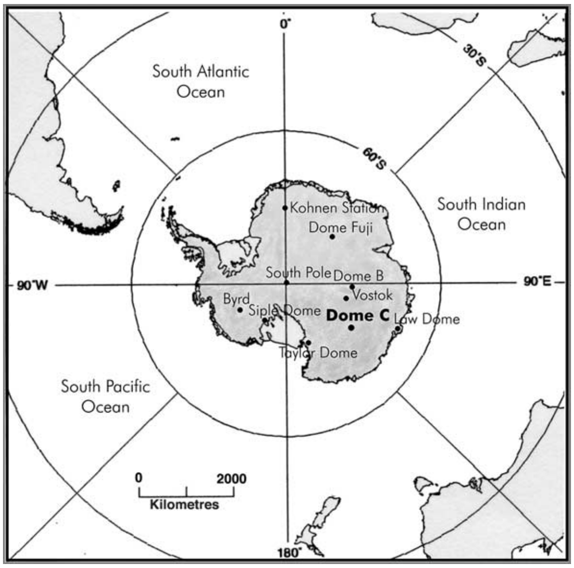

Fig. 1. Map of Antarctica showing the location of selected deep ice cores.

scales, spanning the last millennium [30], the last deglaciation [31], and the past several glacial cycles [32,33] in various Greenland and Antarctic ice cores (GRIP, EPICA Dome C and Vostok). Detailed *d* records spanning the late glacial period have been previously published for old Dome C [34] and Vostok [32], with preliminary data available for Dome F [26].

The sector of Antarctica between 90°E and 180°E is well-represented by three ice cores on the Antarctic Plateau, old Dome C, Vostok and Dome B. Yet for the late glacial period, old Dome C isotopic data have a low temporal resolution (~200 yr) and the Vostok 3G core is of poor quality with numerous damaged or missing sections. The deuterium excess record from the latter was also of low resolution because it was measured on five combined successive 1-m samples [32] providing a low-resolution profile (~400 yr). Finally, the Dome B core does not extend beyond 30 kyr BP [24].

We have recently obtained high-resolution records of both δD and δ^{18}O at the EPICA Dome C site located in this sector (Fig. 1). These profiles, previously published for the last 27 kyr, now span the last 45 kyr, with a time resolution better than 50 yr for the late glacial period. After a short presentation of the data and core chronology, we compare the EPICA Dome C deuterium and deuterium excess profiles with old Dome C and Vostok profiles and then focus on their combined interpretation in terms of site and source temperature fluctuations. Finally, we further examine the link between the source/site temperature gradient [31] and the sodium and calcium records available on the same core [35].

2. Data, ice core chronology and comparison with other isotopic records

The first EPICA Dome C core (75°06′04″S, 123°20′52″E, elevation 3233 m a.s.l., mean annual surface temperature −54.5°C, mean annual accumulation rate 25.0 kg m^{-2}yr^{-1}) was drilled in two field seasons. Unfortunately, the drill got stuck at a depth of 788 m during the second season (1998–1999). Drilling operations had to be resumed from the surface and this second drilling [36] reached the depth of 3200 m at the end of the 2002–2003 field season. Deuterium [37] and deuterium excess [31] profiles have already been published for the upper part of the first core, hereafter EDC96, and sampled down to 585 m during the 1997–1998 drilling season. New deuterium and oxygen 18 data presented in this article cover the additional 200 m of EDC96, recovered one year later. The isotopic measurements were carried out with a depth resolution of 55 cm (bag samples) with 370 new measurements down to the bottom of the core. Analytical methods are as described in [37] and [31] with an accuracy (1σ) of ±0.5‰ and ±0.05‰ for δD and δ^{18}O respectively (both being expressed in per mil with respect to V-SMOW, the Vienna Standard Mean Ocean Water). The resulting accuracy for the deuterium excess is of ±0.7‰.

The EPICA Dome C core chronology (hereafter EDC1) was established combining an ice flow and an accumulation model, using two reference ages and additional information for the Holocene [38]. One tie point corresponds to the end of the Younger Dryas, 11.5 kyr BP [39], as inferred from a comparison with the Byrd records, and the other to the ^{10}Be peak for which an age of

41 ± 2 kyr BP is assigned derived from the dating of the coeval Laschamp magnetic event [40]. Because the δD record for the section deeper than 580 m was not previously available to estimate snow accumulation rates, which are required for establishing a chronology, Schwander et al. [38] inferred this EDC1 δD record from the old Dome C record. The recalculated chronology using measured δD does not differ by more than 100 yr from the published chronology of Schwander et al. [38] and is therefore adopted here without further modification. Note that the age assigned to the ^{10}Be peak has been recently checked [20] due to high-resolution ^{10}Be measurements performed on the EDC96 core by Raisbeck et al. [18]. These authors show that the EDC96 ^{10}Be peak straddles a subdued analogue of the Greenland D/O 10 event, now accurately dated from a precise U/Th chronology performed on a speleothem from western Europe [20]. This chronology places D/O 10 between 40.4 and 41.5 kyr BP and, given the high accuracy of the U/Th method (± 0.4 kyr for 1σ), confirms the previous age assignment of the ^{10}Be peak by Schwander et al. [38]. One can assume a dating accuracy of ± 1 kyr for EDC96 around 40 kyr BP but the dating accuracy decreases and becomes more difficult to estimate above and below the Laschamp ^{10}Be peak. We follow Schwander et al. [38] in claiming that it should not exceed ± 2 kyr over the entire late glacial period that is examined here, based on the fact that the dating inferred from an event (fluoride peak) occurring around 17 kyr BP is well within this uncertainty.

The entire 45 kyr δD and deuterium excess records (raw data) obtained from the EDC96 ice core are reported in Fig. 2A,B, respectively, where they are compared to Vostok and old Dome C profiles. The new data, spanning the period from 27.7 to 44.8 kyr BP, show a marked positive peak in the deuterium profile centred at about 37.5–38 kyr BP. This event, referred to as A1, has already been observed in other Antarctic ice core records [5] and it can be inferred that the very bottom of the EDC96 core, i.e. from 43.6 to 44.8 kyr BP, corresponds to the end of oscillation A2, as now fully confirmed from data obtained on the EDC99 core [41]. There are three well-marked oscillations between A2 and A1 and a series of millennial oscillations superimposed on a decreasing δD trend from A1 until ~25 kyr BP. There is no clear δD trend from then to the time of the Last Glacial Maximum (LGM, around 20 kyr BP), with lowest values and superimposed smaller oscillations observed between 28 and 18 kyr BP, when deglacial warming begins in this

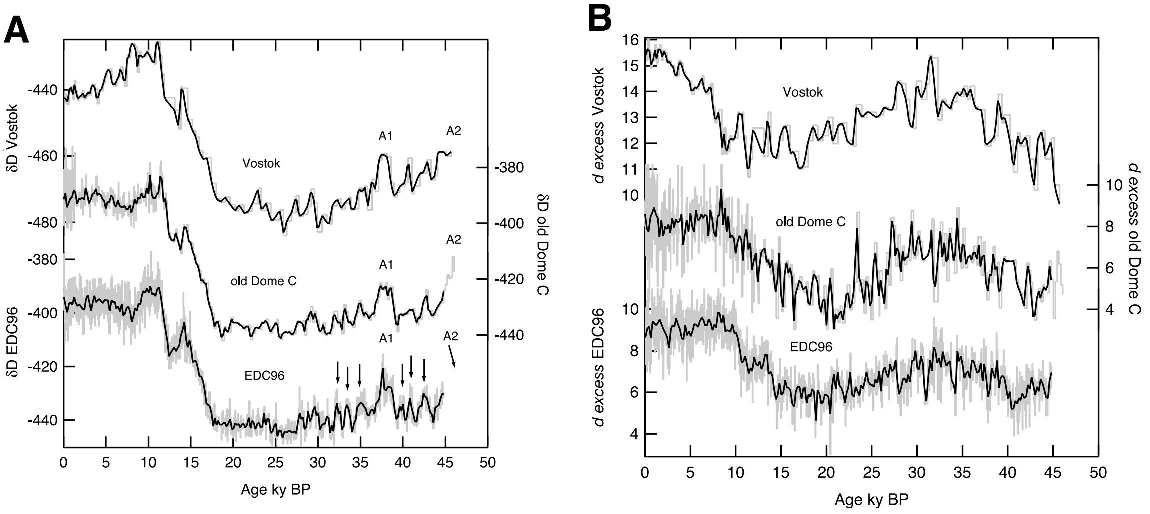

Fig. 2. Deuterium (A) and deuterium excess records (B) of EDC96, old Dome C and Vostok placed on the EDC1 time scale. The raw measurements (grey lines) and the 200-yr resampled data (black lines) are displayed for each record. The arrows refer to glacial events identified as subdued analogues of D/O events (see text).

core. The deuterium excess values (Fig. 2B) increase from an average minimum of about 5‰ at 41 kyr BP toward a near-Holocene value of 9‰ at about 32.5 kyr BP. Quite high values, around 7–8‰, are observed up to 27.7 kyr BP. Afterwards, a decreasing trend is observed reaching again a broad minimum of 5‰ at 18 ± 2 kyr BP.

The EDC96 δD and deuterium excess records resampled to a 200-yr time step are reported in Fig. 2A,B along with the corresponding Vostok and old Dome C profiles. For the purpose of this comparison, we have chosen EDC1 as a common time scale. The old Dome C profiles are placed on the EDC1 time scale by visually aligning δD features in the old Dome C and EPICA Dome C cores. A common time scale is developed for Vostok using 145 common volcanic horizons identified in the sulphate and electrical conductivity measurement (ECM) records of EDC96 and in the ECM record of Vostok (Udisti et al., in preparation). Both the original old Dome C and the GT4 Vostok time scales are significantly younger than EDC1, which is the direct result of the age assigned to the ^{10}Be peak that was used to derive the old Dome C and Vostok chronologies. After accounting for these chronological discrepancies, the excellent agreement observed during the deglaciation [37] between the EDC96, Vostok and old Dome C δD profiles is still valid for the glacial (Fig. 2A): most of the oscillations occurring during the glacial are recognised in all δD records but they are more clearly defined in the EDC96 profile due to its higher resolution, the excellent quality of the core and improved analytical precision. The remarkable similarity between these isotopic fluctuations suggests a common atmospheric climate history during the late glacial and the deglaciation over this part of the East Antarctic Plateau. As already noted in [37], there is an offset of about 5‰ between EDC96 and old Dome C δD. This isotopic difference is attributed to more intense isotopic distillation at EPICA, with more depleted isotopic values and smaller accumulation rates at the EPICA site (typically 15% less) than at the old Dome C [37].

Fig. 2B displays the comparison between old Dome C [34], EDC96 and Vostok [32] deuterium excess records with both raw data and 200-yr resampled data. As expected, the two records obtained at Dome C show similar fluctuations with a systematic offset, as for deuterium, due to slightly different locations and isotopic distillations. The comparison with Vostok deuterium excess data highlights the high resolution of the new record discussed here. Vostok and EDC96 deuterium excess variations show the same low frequency variability during the glacial time from 45 to 20 kyr BP with a relative maximum at about 31–32 kyr BP but with a larger amplitude of this maximum for Vostok (5‰) than for EDC96 (3‰). However, they differ at the bottom of the record (40–45 kyr BP), during the deglaciation and the Holocene, with a delayed increase in Vostok compared to Dome C. EDC96 deuterium excess values increase from 16 kyr to 8 kyr BP and remain rather flat during the Holocene. In contrast, Vostok deuterium excess values start to increase later, at ∽12 kyr BP, and continue to rise through the Holocene.

3. Methodology of site and source temperature reconstructions

The deuterium excess of water vapour above the ocean depends on parameters controlling the kinetics of the phase changes [42], principally on the temperature and relative humidity at the evaporative source, and, to a lesser degree, on wind speed. In turn, the deuterium excess contains information about conditions prevailing in the source regions. Application of a simple Rayleigh-type model, as derived by Ciais and Jouzel [43], shows that the δD content of Antarctic snow depends primarily on the temperature of the site, T_{site}, and to a lesser degree on the average source temperature, T_{source}. The reverse holds for the deuterium excess. The application of an inversion method thus allows the extraction of both T_{site} and T_{source} once δD and δ^{18}O data are measured. This has been applied to the GRIP [30] and Vostok [33,44] cores as well as to the upper part of the EPICA Dome C core [31].

Here, we extend this approach to reconstruct past surface temperature changes at the EPICA

Dome C site and in the main moisture sources which, from the model approach of Delaygue et al. [45], should be located around 40°S in the Indian ocean. The Rayleigh model is tuned [46] by adjusting parameters controlling the threshold for solid precipitation and the supersaturation function in order to correctly simulate the modern isotopic values along the 1995–1996 traverse from Dumont d'Urville to Dome C [47]. The model is then run with varying site and source temperatures neglecting the influence of both relative humidity and wind speed changes. We account for the change in the δD and $\delta^{18}O$ values of surface seawater based on the $\delta^{18}O_{sw}$ of Waelbroeck et al. [48]. This source isotopic composition results in a smaller change at the precipitation site, proportional to 8 $(1+\delta D)$ [27]. For the Dome C site, the corrected δD and $\delta^{18}O$ values (expressed as deviations from the present-day values) are well approximated by:

$$\Delta\delta D_{corr} = \Delta\delta D - 5.0\Delta\delta^{18}O_{sw} \quad (1)$$

$$\Delta d_{corr} = \Delta d + 2.6\Delta\delta^{18}O_{sw} \quad (2)$$

The model is run assuming a constant relationship between condensation and surface temperature [49]. The order of magnitude of the $\delta^{18}O_{sw}$ correction has the same amplitude as the glacial–interglacial deuterium excess signal (an LGM correction of +2.7‰ to compare with a glacial deuterium excess decrease of 4‰) but only a weak impact on the deuterium (an LGM correction of −5‰ compared to a glacial deuterium decrease of 45‰). Once corrected for this seawater effect, the following linear regressions between simulated Dome C isotopes and site and source temperatures are obtained:

$$\Delta\delta D_{corr} = 7.6\Delta T_{site} - 3.6\Delta T_{source} \quad (3)$$

$$\Delta d_{corr} = -0.5\Delta T_{site} + 1.3\Delta T_{source} \quad (4)$$

As a result, the site and source temperatures are extracted from the isotopic profiles with:

$$\Delta T_{site} = 0.16\Delta\delta D_{corr} + 0.44\Delta d_{corr} \quad (5)$$

$$\Delta T_{source} = 0.06\Delta\delta D_{corr} + 0.93\Delta d_{corr} \quad (6)$$

Note that the slope between ΔT_{site} and $\Delta\delta D_{corr}$ is nearly identical to present-day precipitation (1/6.04 = 0.16°C/‰) [50]. This probably results from the simultaneous change in site temperature and moisture source temperature along trajectories from the Antarctic coast to the inland plateau, as suggested by atmospheric models that trace air mass trajectories [45]. Indeed, at coastal locations, moisture is transported from surrounding waters by low-altitude atmospheric circulation, whereas high-altitude moisture transport carries lower-latitude moisture further inland.

4. Discussion

We will focus the discussion: (i) on the comparison between the EPICA Dome C and Vostok deuterium excess records and (ii) on the late glacial period examining successively the ΔT_{site} and ΔT_{source} characteristics.

We then discuss changes in the source and site temperature and source-to-site temperature gradient with respect to changes in concentration of aerosols [35] measured in the same ice core.

4.1. Vostok–Dome C deuterium excess comparison

Two factors may account for the 6–7‰ higher excess levels at Vostok compared to Dome C:

1. a larger kinetic effect at snow formation due to colder conditions at Vostok than Dome C, as suggested by Petit et al. [51];
2. different moisture transport patterns with a larger contribution of remote low-latitude moisture transported at higher altitudes to the more inland site of Vostok. General circulation models indicate that low-latitude moisture is transported at higher altitudes to the inland plateau of East Antarctica, with a progressive warming of the mean moisture source from the Antarctic coast toward the central plateau [45].

As already noted for Vostok [32], the low-frequency deuterium excess variability during glacial time (from 45 to 20 kyr BP), observed in both Dome C and Vostok records (Fig. 2B), appears to be strongly influenced by obliquity fluctuations which are expected to alter the meridional temperature gradient between low and high latitudes. Decreasing obliquity, such as that from 45 to 29 kyr BP, produces opposing mean annual insolation changes at the top of the atmosphere at latitudes above and below ~45°S, with the low latitudes receiving more solar radiation and the high latitudes less. The inverse correlation between deuterium excess and obliquity ends during the deglaciation in the EPICA Dome C record.

The different behaviour observed during the deglaciation and the Holocene may be due to a larger contribution of tropical moisture to Vostok precipitation during warm periods (moisture being transported at higher atmospheric levels) compared to Dome C. Obliquity changes would be expected to have a limited effect on moisture sources located around 40–45°S compared to lower-latitude moisture sources. However, the flatness of the Vostok deuterium excess during the deglaciation could also be due to a compensation effect of a parallel increase of both site and source temperatures [33].

4.2. Site temperature

In Fig. 3 we report ΔT_{site} as derived from the inversion (Eq. 5) and as calculated by the conventional method ($\Delta T_{\delta D}$) based on the use of the present-day observed temperature/isotope slope (6.04‰/°C) [50]. As pointed out in [27] the conventional approach and the inversion procedure, which corrects for source temperature changes, provide similar estimates of glacial–interglacial temperature changes in East Antarctica. Indeed, the source temperature correction based on the seawater-corrected deuterium excess leads to a small change of the site temperature (between −0.5 and +1.2°C) between 27 and 45 kyr BP. This is due to the small value of Δd_{corr} which itself results from the above-mentioned compensation of the deuterium excess change and of the seawater isotopic composition correction. When discussing the impact of source changes on the reconstructed glacial Antarctic temperature, two points are of interest.

First, Mazaud and co-workers [52] drew attention to the possibility that events such as A1 and A2 recorded in the isotopic Antarctic records (Byrd, Vostok, Dome C) and commonly interpreted as reflecting warmings in Antarctica, could at least partially correspond to a temporary cooling of the source water for Antarctic precipitation. Vimeux and co-workers [33] recently pointed out that this was not the case at Vostok. Here, we

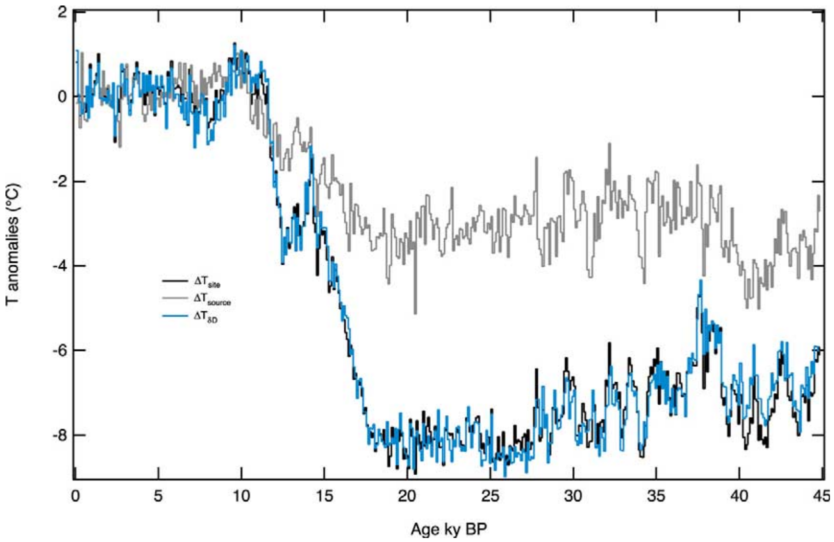

Fig. 3. Reconstructed site (ΔT_{site}, black line) and source (ΔT_{source}, grey line) temperatures anomalies (in °C, centred onto modern values) using the full inversion and using the classical palaeothermometry method ($\Delta T_{\delta D}$, blue line). Results are displayed with a 100-yr time resolution.

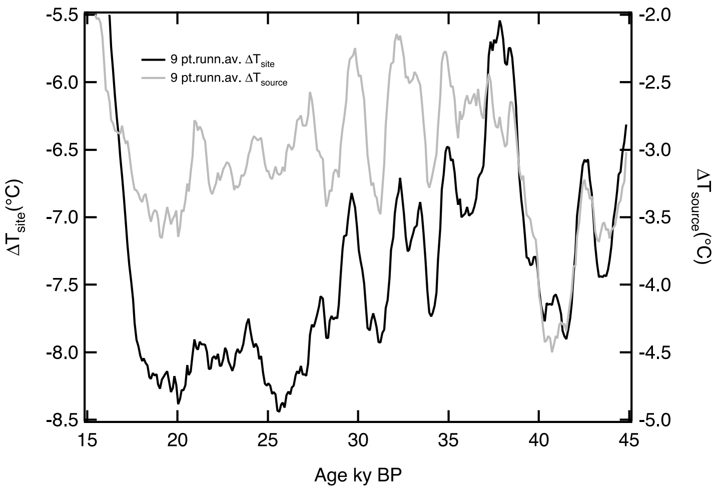

Fig. 4. Glacial site (ΔT_{site}, black line) and source ($\Delta T_{\mathrm{source}}$, grey line) temperature variability reconstructed from EPICA Dome C ice core. The EPICA temperature results are displayed as nine-point running averages performed on 100-yr time step data.

confirm this latter result for the EPICA Dome C site which shows no significant difference in the size of A1 or any late glacial warm event before and after correction for source temperature changes (Fig. 3).

Second, there is a correspondence between the late glacial events recorded at EPICA Dome C and the successive D/O events recorded in the Greenland isotopic records. The possibility of such a correspondence, first pointed out for the largest events by Jouzel et al. [2] and Bender et al. [3] comparing the Vostok and Greenland records, was later extended to minor events [4]. Here this correspondence is much easier to establish than for Vostok because of the higher resolution and the better quality of the EPICA Dome C isotopic record. This was already noted by [18] for the features between A1 and A2 (A1 corresponding

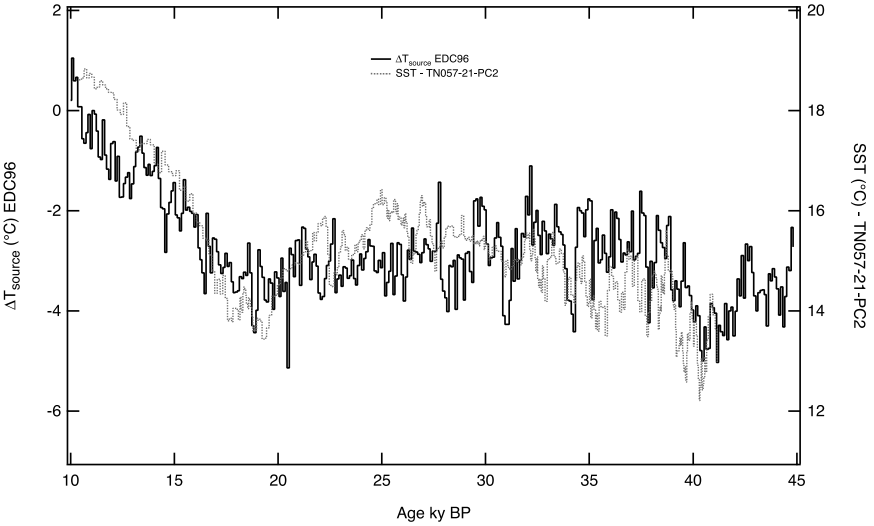

Fig. 5. Comparison between EPICA source temperature ($\Delta T_{\mathrm{source}}$, 100-yr time step data, black line) and southeast Atlantic sea surface temperature from TN057-21-PC2 deep-sea core (raw data from [53], grey dotted line) placed on their own chronologies.

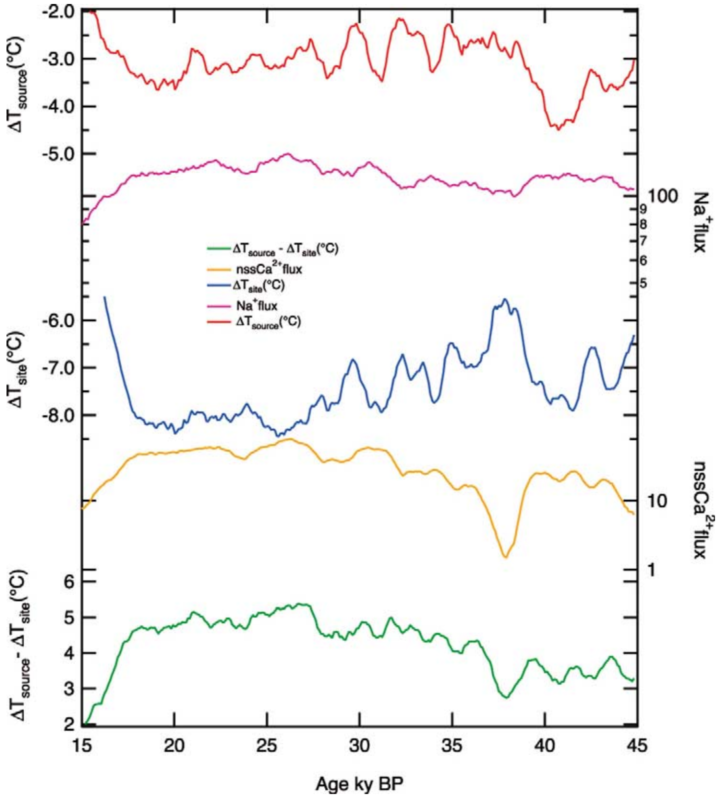

Fig. 6. Site (ΔT_{site}), source ($\Delta T_{\mathrm{source}}$) and gradient ($\Delta T_{\mathrm{source}}$–$\Delta T_{\mathrm{site}}$) temperature anomalies compared to aerosol fluxes (ng/cm^2/yr) derived from the Na^+ and nssCa^{2+} concentrations measured in the EPICA ice core. The results are displayed as nine-point running averages performed on 100-yr time step data.

to D/O 8 and A2 to D/O 12). Based on their position and pattern, these small events can be identified as subdued analogues of D/O 9–11. This is illustrated in Fig. 2A (see arrows) where visual identification of D/O events can be extended to include events 7–5. Obviously, such an identification based on the morphology of the isotopic profiles does not tell us about the exact timing of those Antarctic events (see [4–6,18]), an aspect which will be fully discussed elsewhere.

4.3. Source temperature

The source temperature profile (Fig. 3) shows different long-term trends during the glacial period than the site temperature profile. It exhibits a 1.5°C decrease from 45 to 41 kyr BP and then a rise of 2°C to a broad maximum that extends to 28 kyr BP, with values about 1°C above the LGM level. As already noted for Vostok [32] the slow source temperature fluctuations likely reflect the changes in annual mean insolation caused by changes in the Earth's tilt. The minimum obliquity, at about 29 kyr BP, corresponds to warmer low latitudes (and colder high latitudes), and results in an increase of deuterium excess values due to a larger contribution of low-latitude moisture sources to polar precipitation. During the A1 event, the site and source temperatures are not in phase (Fig. 4), leading to a decreased latitudinal temperature gradient. Apart from the A1 event, the other smaller millennial-scale temperature fluctuations appear to be in phase between site and source temperatures.

Since the moisture source can be spatially variable in time, the aim is not to reconstruct a local sea surface temperature. However, the reconstructed source temperature shows a remarkable similarity, in both trends and magnitudes, to a recent high-resolution sea surface temperature record obtained from alkenone palaeothermometry conducted on a deep-sea sediment core drilled in the southeast Atlantic (core TNT057-21-PC2 [53]). The similarity during the last deglaciation, already noted by Steig [54], remains valid during the glacial time (Fig. 5): both records share a strong cooling at 41 kyr BP followed by an increase to temperatures significantly above the glacial maximum level. The maximum values are reached significantly later for the south Atlantic record, suggesting possible delays between temperature changes in the EPICA moisture source (most probably located in the south Indian Ocean) and the south Atlantic. The similarity between our 'delocated' reconstruction and the sea surface temperature reconstruction of Sachs et al. [53] supports the quantitative source temperature reconstructed by our simple inversion method, even if crude assumptions are being used.

4.4. Latitudinal temperature gradient

A smoothed profile (nine-point running averages performed on 100-yr time step data) of the reconstructed source-to-site temperature gradient, $\Delta T_{\mathrm{source}}$–$\Delta T_{\mathrm{site}}$, is displayed in Fig. 6. Due to the different trends in site and source temperature changes, the latitudinal temperature gradient exhibits a marked decrease during the A1 event, followed by a progressive increase until about 27 kyr BP, when it reaches its maximum value, and high values up to 18 kyr BP. In addition to the progressive increase, attributable to obliquity changes which modulate the meridional annual mean insolation gradient, two large events are observed: first, the large decrease during A1 at 38 kyr BP; second, a large increase from 28 to 24 kyr BP. This second event corresponds to cold conditions in Antarctica with intermediate source temperature levels.

As the atmospheric circulation tends to transport heat and moisture to counteract such large meridional temperature gradients [55], the intensity of the atmospheric transport should be at least partly related to our reconstructed meridional temperature gradient.

It is conceivable that an increase in atmospheric circulation has an effect on aerosol uptake and transport. However, there are factors other than atmospheric circulation that may exert a strong influence on aerosol flux at Dome C. In Fig. 6, smoothed profiles (nine-point running averages performed on 100-yr time step data) of sodium (Na, a proxy for sea salt) and non-sea-salt calcium (nssCa, a proxy for continental dust) fluxes are shown together with ΔT_{site}, $\Delta T_{\mathrm{source}}$ and $\Delta T_{\mathrm{source}}$–$\Delta T_{\mathrm{site}}$ profiles. The overall modulation of the Na flux is small and barely related to the source and site temperatures or to the temperature gradient ($r^2 < 0.3$). In contrast, the changes in nssCa flux are much more pronounced, which are similar to the site temperature and temperature gradient ($r^2 = 0.50$ and $r^2 = 0.55$ respectively). However, a recent study [35] concluded that the changes in nssCa flux during the A1 event do not primarily reflect atmospheric transport but rather changes at the dust source. If the changes in nssCa were a result of atmospheric transport variation, one would expect to see an effect on sea salt aerosol too. On the other hand, the dust source is presumably fairly sensitive to changes in humidity and precipitation, which could be related to changes of the temperature gradient. For Na it seems as if other controls are stronger than the change in circulation induced by a variation of the temperature gradient. Recently, it has been suggested that Na flux is related to sea ice production around Antarctica [56]. Warmer temperatures at the moisture source might coincide with conditions less favourable for sea ice production and therefore with slightly lower Na flux.

5. Conclusions

Despite numerous existing data, there is still a strong interest in obtaining new high-resolution climate records from the last glacial period from both continental and marine environments. In this context, we present reconstructions of local site temperatures and distant moisture source temperatures for the EPICA Dome C ice core in central East Antarctica spanning the last 45 kyr. The reconstructed ΔT_{site} is characterised by a cooling trend from the A1 warm event (38 kyr BP) until the LGM. The $\Delta T_{\mathrm{source}}$ profile increases from 41 to 32.5 kyr BP, remaining quite high until 28 kyr BP, and then decreases until the LGM (∼20 kyr BP). As a result, we observe an increasing trend of the calculated temperature gradient from 38 to 27 kyr BP. The impact of changes in source conditions on the reconstructed site temperature remains small and does not modify the shape of the A1 event, still appearing as a warming in Antarctica.

Our 'non-conventional' 'delocated' source temperature profile shows remarkable similarities with a high-resolution sea surface temperature record from 41°S latitude in the southeast Atlantic [53], providing support for our interpretation of slow deuterium excess fluctuations in terms of changes in moisture source temperature resulting from changes in annual mean insolation and, by extension, obliquity.

The pronounced changes in the nssCa flux to central East Antarctica during the late glacial period, in contrast to small changes in the Na flux, and the comparison with the temperature profiles (site, source and gradient) suggest that the aerosol variations are only partly related to changes in atmospheric transport.

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