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Homogeneous climate variability across East Antarctica over the past three glacial cycles

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Recent ice core studies have raised the disturbing possibility that glacial–interglacial climate changes may be non-uniform across Antarctica[1,2]. These findings have been confined to records from the Ross Sea sector of the continent, but significant deviations in other areas would call into question the widely assumed validity of the climate record obtained from Vostok, East Antarctica, on large spatial scales[3]. Here we present an isotopic profile from a core drilled at Dome Fuji[4,5], situated 1,500 km from Vostok in a different sector of East Antarctica. The two records show remarkable similarities over the past three glacial cycles (the extent of the Dome Fuji record) in both large-amplitude changes, such as terminations, interglacials and interstadials and more subtle glacial events, even when the origin of precipitation is accounted for. Our results indicate that Antarctic climate is essentially homogeneous at the scale of the East Antarctic Plateau, possibly as a consequence of the symmetry of the plateau and the adjacent ocean.

Climate records extending at least back to the Last Glacial Maximum, 20 kyr BP (thousands of years before present), have now been recovered from deep ice cores drilled at seven different Antarctic sites (Fig. 1). The inland East Antarctic records (Dome C, Dome B and Vostok, with two published series at Dome C and Vostok) are very similar where they overlap, with a deglaciation history characterized by a long gradual warming interrupted by the Antarctic Cold Reversal, clearly preceding the North Atlantic Younger Dryas[6]. These characteristics are shared by the records from Byrd[7] (inland West Antarctica) and Law Dome (coastal East Antarctica)[8]. Although the exact timing of the Antarctic Cold Reversal is still debated[8], all these records show a deglacial pattern very different from that registered in Greenland cores. In contrast, the records from Taylor Dome[1] and Siple Dome[2], two near-coastal sites in the Ross Sea sector (Fig. 1), show Greenland-like features with indication of either climate changes synchronous with the North Atlantic[1] or of very rapid changes typical of the Greenland record[2].

Here we present a climate isotopic record from a core successfully recovered by Japanese drillers in 1995 and 1996 at Dome Fuji in East Antarctica[4], which, in this context, is important for at least two reasons. First, Dome Fuji and other inland East Antarctic sites are located in completely different sectors of East Antarctica (Fig. 1). Second, the Dome Fuji core extends back to about 330 kyr BP (ref. 9). It provides the second-longest climate time series after the Vostok cores, allowing a detailed comparison over the last three glacial–interglacial cycles, including three successive deglaciations (Fig. 2). Ongoing Dome Fuji studies provide a wealth of new and detailed information in various fields (climate, atmospheric chemistry, atmospheric composition, ice properties and ice dynamics).

We focus on the continuous ^{18}O profile in ice ($\delta^{18}O$) and on its comparison with the Vostok deuterium record[3] (δD). We also shortly discuss implications of the two deuterium-excess profiles ($d = \delta D - 8 \times \delta^{18}O$) in terms of local temperature interpretation.

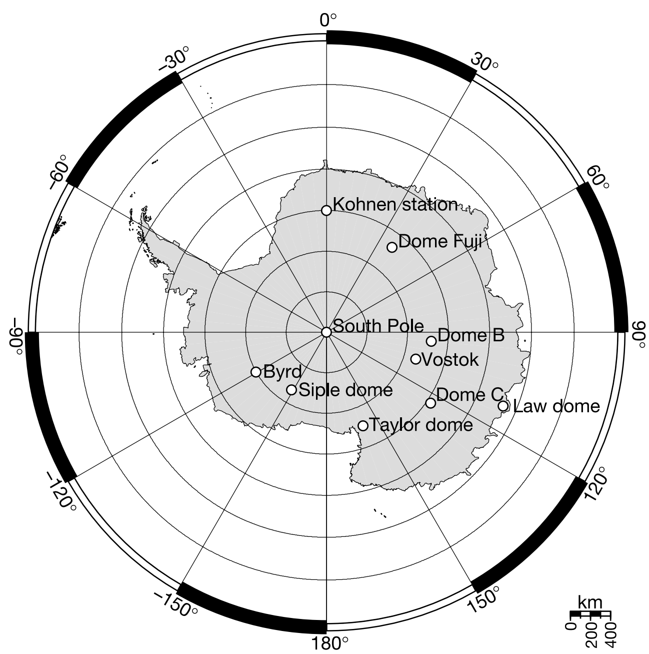

Figure 1 Map of Antarctica with indication of the deep drilling sites. The Dome Fuji site is located about 1,000 km from the coast at the highest point of the East Dronning Maud Land Plateau: 3,810 m above sea level (a.s.l.), accumulation $\sim$2.7 g cm^{-2} yr^{-1}, 10-m depth temperature of -58 °C (ref. 9). The core covers 2,503 m, whereas the ice thickness is 3,090 m.

The similarities between the inferred Dome Fuji and Vostok climate records, which hold for the whole period and even for very detailed features, are remarkable given the distance between the two sites (about 1,500 km) and a plausible different precipitation origin.

Glaciologists rely on the δD or $\delta^{18}O$ composition of the ice to reconstruct continuous records of past temperature changes, ΔT_s. The two parameters are linearly related with a slope close to eight[10] and both may be used interchangeably. A different choice was made by the Vostok and Dome Fuji teams who used δD and $\delta^{18}O$ for temperature reconstruction (see Methods), respectively. Figure 2 shows these isotopic profiles as a function of depth and age, whereas inferred ΔT_s values are compared in Fig. 3. The deepest Dome Fuji samples correspond to the last part of termination IV, dated at about 340 kyr BP in the deep-sea core chronology[11].

To compare the Dome Fuji and Vostok climatic records, we placed them on a common timescale. We adopted the Dome Fuji timescale obtained by the inverse method developed in ref. 12, an approach ideally suited for dating a core located on a dome (see Methods). To transfer the Vostok record onto the Dome Fuji timescale, numerous tie points can be defined but we prefer to use only a few and interpolate between them (Fig. 2), to examine how other events correlate. The similarity between the two records is remarkable. Large interglacials, interstadials and smaller events are quite similar both in shape and amplitude in the two records. There are a few noticeable exceptions. The low values around 45 kyr BP are more pronounced at Vostok than at Dome Fuji and vice versa around 100 kyr BP. The peak just before 175 kyr BP is clearly marked at Dome Fuji and muted at Vostok whereas the situation is reversed

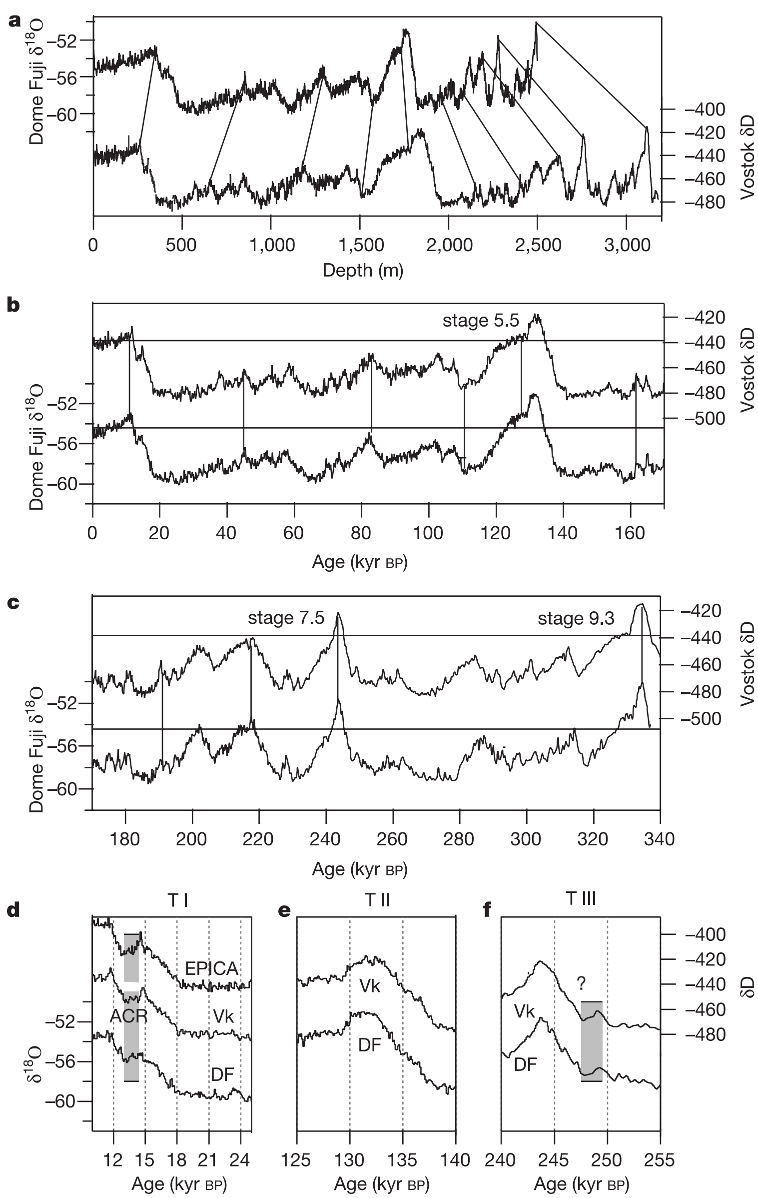

Figure 2 Comparison of the Vostok and Dome Fuji isotopic records as a function of depth and time. For the sake of visual comparison δD and $\delta^{18}O$, expressed in per mil units with respect to VSMOW, the Vienna Standard Mean Ocean Water) are scaled in a ratio of 7.94 which corresponds to the Vostok $\delta D/\delta^{18}O$ slope[10]. We use the inverse Dome Fuji timescale on which the Vostok record is transferred using the tie points of **a**, and a linear interpolation with respect to age rather than to depth because the thinning function differs between the two sites. For this comparison the two records have been resampled at equally spaced intervals of 100 years. Vertical lines (in **b** and **c**) correspond to the tie points shown in **a**, and horizontal lines correspond to the mean Holocene isotopic content for each core. The Vostok deuterium profile is shown down to 3,200 m in order to include the end of marine stage 10 and termination IV. **d**–**f**, Expanded views of terminations I, II and III. For termination I (**d**), we have also reported the EPICA Dome C deuterium record[6]. ACR, Antarctic Cold Reversal; Vk, Vostok; DF, Dome Fuji.

for the peak just before 300 kyr BP. The coldest part of the third climatic cycle seems to start about 7 kyr earlier at Dome Fuji than at Vostok but this is clearly due to the small number of tie points. We could list other examples but overall those differences are relatively minor and might even be readily explained by depositional noise, in such low accumulation areas.

At Vostok the coldest part of each glacial period occurred just before the termination with the noticeable exception of the third cycle. Termination III, starting at ~248 kyr BP for its main rise, is preceded by a series of three short events. Exactly the same sequence is observed at Dome Fuji with a small but well-marked event between 251 and 248 kyr BP. As a result, we can consider termination III (Fig. 2f) to be a two-step transition similar to termination I (Fig. 2d) but with a Cold Reversal at the very beginning of this transition; we would expect confirmation either from other properties or from another core such as EPICA Dome C[13]. In contrast, termination II (Fig. 2e) is very regular both at Vostok and Dome Fuji where termination I (Fig. 2d) shows a two-step warming with a first trend ending slightly before 14.5 kyr BP. The Antarctic Cold Reversal has its coldest part just before 13 kyr BP and is then followed by a second warming trend starting around 13 kyr BP, about 1.5 kyr before the end of the Younger Dryas. Similarities with other inland East Antarctic cores extend to the early Holocene epoch, characterized by a clear optimum at 12–9 kyr BP (ref. 14).

At both sites, warm interglacials (marine stages 9.3, 7.5 and 5.5) are followed by increasingly colder interstadial events that end with a rapid return towards the following interglacial. As in the Vostok record, the Dome Fuji record confirms that interglacials 9.3 and 5.5 are very similar in duration, shape and amplitude but differ both from the Holocene and from interglacial 7.5. This is illustrated in Fig. 3a, which compares the two isotopic records directly in terms of local temperature, applying the conventional approach based on present-day observations[3,15] (see Methods). Unlike for the Greenland record, the use of this spatial slope as a surrogate of the temporal slope in central East Antarctica appears justified within ±20% (ref. 15).

As reviewed in ref. 15, this is largely because glacial–interglacial changes in the seasonality and in the origin of the precipitation have no strong influence on the temporal slope. Both aspects have been

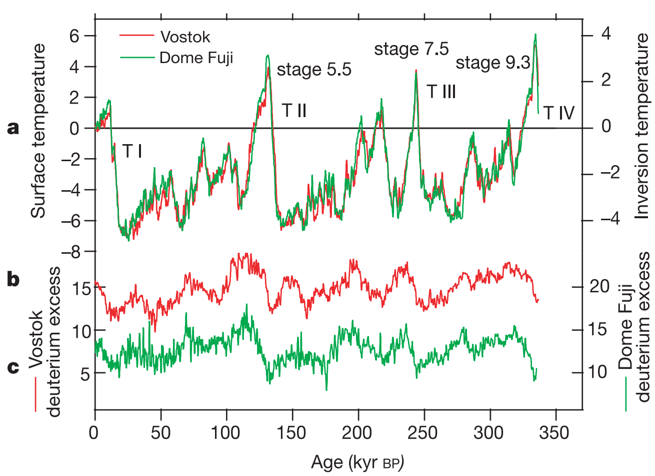

Figure 3 Comparison of the Dome Fuji and Vostok isotopic temperature and deuterium-excess[10,25] records. **a**, The surface, ΔT_s, and inversion, ΔT_i, temperature (°C) differences, with $\Delta T_i = 0.67\Delta T_s$ (ref. 15) with respect to the last 1,000 years. The curves are smoothed versions of the temperature records inferred from the isotopic records (see Methods) with further small time adjustments with respect to Fig. 2b, c. Terminations I to IV and marine stages are shown. **b**, **c**, The smoothed Vostok and Dome F deuterium-excess records (‰ VSMOW). All these curves are obtained using an 11-points least-squares smoothing performed on a 100-yr resampled time series.

examined using a variety of modelling approaches[16,17], and this result is supported overall by experiments performed with isotopic General Circulation Models[15,18]. Even when such experiments show noticeable differences in the oceanic origin of the Vostok and Dome Fuji precipitation, they do not seem greatly to affect ΔT_s estimates[17]. This can be independently evaluated when both δD and $\delta^{18}O$ profiles are available, with a correction expressed as a function of the change in deuterium-excess[10,19]. Because of less continuous sampling at Dome Fuji at present, the excess record shows much higher variability than at Vostok and we thus compare, in Fig. 3, smooth versions of this parameter. These profiles show glacial–interglacial changes of relatively similar amplitude and shape. In turn, accounting for this source correction, which is in any case relatively small, does not significantly alter the similarities between estimated local temperature changes (see Methods).

As for the Vostok record, the peaks of stages 9.3, 7.5 and 5.5 were warmer at Dome Fuji than during the Holocene, but they appear also to be systematically warmer than the corresponding Vostok peaks (by more than 1 °C for stage 9.3). Dome Fuji should provide a better record than Vostok where deeper ice originates more than 200 km upstream of the drilling site. Although an explanation based on an elevation change cannot be definitely ruled out, we tentatively assumed that this Dome Fuji / Vostok surface temperature difference relates to the origin of the Vostok ice, and applied a slight correction to the Vostok profile accordingly (see Methods). In turn, interglacial 9.3 was probably the warmest period over the last 400 kyr in Antarctica with maximum surface temperature up to 6 °C warmer than during the Holocene. Not only is there a high degree of similarity between the two temperature records (Fig. 3a) given the distance between the two sites (with a correlation coefficient R^2 of 0.96), but also the overall amplitude of change is exactly the same at both sites.

This similarity further reinforces the validity of using the conventional approach because if its application were biased (either at Vostok or at Dome Fuji, or at both sites) owing to changes in precipitation seasonality, such variation would not be completely uniform over a spatial scale of 1,500 km. Alternatively, these strong isotopic similarities may occur by chance; we cannot definitely exclude the possibility that ΔT_s does differ between the two sites but that the isotopic records nevertheless have a similar amplitude owing to some compensation effect. Whatever the correct explanation, Fig. 3a clearly supports the conclusion[3] that the broad features of the Vostok record are of geographical significance for a large area (Antarctica and part of the Southern Hemisphere).

The present study thus considerably extends previous work both geographically and temporally. Dome Fuji and Vostok records show a remarkably high degree of similarity given that three climatic cycles are depicted at two sites from different sectors of East Antarctica. Successive terminations and large interglacial events as well as intervening large interstadials have comparable shape. This applies to termination I, strongly suggesting that Greenland-like features[1,2] are, in any case, restricted to the Ross Sea sector. Indeed, the Dome Fuji record adds considerably to the geographical significance of the Antarctic Cold Reversal event, until now based mainly on cores located in a sector representing about one-third of East Antarctica[6]. This also applies to smaller events which, for the last glacial period[20,21], are counterparts of the Dansgaard–Oeschger events recorded in the Greenland records[22]. Dome Fuji is closer to the Atlantic Ocean than Vostok, so it is somewhat surprising that those Dansgaard–Oeschger events are not recorded differently in the two sites. However, model experiments in which the origin of water vapour is tagged[23,24] suggest that, at both sites, a significant part of the precipitation originates from the Indian and Pacific oceans. They thus provide a reasonable explanation for observed similarities and reinforce the need for further drillings at sites in the Atlantic sector.

As noted, the comparison between Dome Fuji and Vostok temperature records indirectly supports the conventional interpretation of isotopic records for Antarctica. It suggest that stages 9.5 and 5.5 were much warmer than the most recent 1,000 years (~4.5 °C for stage 5.5 and up to 6 °C for stage 9.3). More importantly, it suggests overall that the Antarctic climate is essentially homogeneous when examined at large geographical (East Antarctic Plateau) and temporal scales. We suggest that this homogeneity of the Antarctic climate at these scales might result from the relative symmetry of East Antarctica and of the adjacent Southern Ocean. However, we expect that examining other ice-core properties will reveal differences due to the oceanic origin of the air masses that provide precipitation at each site.

It will also be interesting to extend this comparison to other Antarctic cores, in particular the Dome C and Dronning Maud Land cores (Fig. 1) currently drilled in the framework of EPICA (European Project for Ice Drilling in Antarctica). Together with Dome Fuji, the Dome C core, which may already cover 520 kyr (ref. 13), will strongly constrain the duration of successive events (such as the last interglacial) and in turn the Antarctic chronology, whereas the Dronning Maud Land core is ideally located (about 1,000 km from Dome Fuji and closer to the Atlantic) to make the link with the Greenland records. □

Methods

The $\delta^{18}O$ concentration was measured over the full length of the Dome Fuji core at the National Institute for Polar Research[5,9] with a depth resolution increasing from its top to its bottom (ice increments from ~2 m for the Holocene period to 10 cm for the third climatic cycle). As a result, the time resolution is, for periods older than ~100 kyr BP, better or much better at Dome Fuji than at Vostok, where δD measurements were performed every metre. For example, the third climatic cycle between interglacials 9.3 and 7.5 is represented by 400 samples (average resolution of 200 years) at Vostok and by ~2,000 samples at Dome Fuji (average resolution of 40 years). The deuterium-excess Dome F profile was obtained from a partly different set of less continuous samples (10–25 cm every 1.85 m on average), measured at the Tokyo Institute of Technology[25].

The inverse dating method[12] combines an accumulation history and an ice flow model, under the assumption that the number of precessional cycles can be correctly counted. This assumption is straightforward for the Vostok deuterium record as well as for the record of atmospheric ^{18}O, strongly influenced by the precession[3]. Rather than having fixed control points[3], the inverse dating method accounts for the uncertainty associated with any chronological information and then identifies glaciological chronologies which best fit this information. It was developed for dating the Vostok ice core, where, however, it fails to provide a reliable timescale beyond the last two climatic cycles. This is probably because accumulation changes upstream of Vostok, from where the Vostok ice originates, are poorly known[12].

In contrast, the Dome Fuji core is ideally suited to develop such a timescale as, unlike for the Vostok record, ice found at depth is formed from snow that accumulates at the site itself. The bottom of the core is also about 600 m above the bedrock, which ensures that the records obtained are undisturbed. However, we can at present rely on orbital constraints derived from the ice $\delta^{18}O$ record only. The inverse Dome Fuji timescale should thus be considered preliminary, as it would be useful to account also for the information contained in the air-bubble ^{18}O. However, we use the timescale here because it is of equal quality over the entire record, confirming for example that the GT4 Vostok chronology is too young for the third climatic cycle[3]. The isotope and temperature records are presented using this Dome Fuji inverse timescale (Figs 2 and 3).

The choice of the timescale is indeed not central for the comparison between Dome Fuji and Vostok climate records on which we focus here. We note that the duration of the last interglacial (stage 5.5) is shorter than in previous Vostok chronologies[3,26], that is, about 14 kyr at mid-transition (Fig. 2d). As for the inverse Vostok dating, the age at mid-transition (~134 kyr BP) is significantly younger than that of 139 kyr BP derived in the initial Vostok dating[26] and thus does not support recent claims for an early termination II[27,28].

The surface-temperature changes displayed in Fig. 3a are derived as follows. Present-day observations show $\delta^{18}O/T_s$ spatial slopes of 0.852‰ per °C in the Dome Fuji sector and of 0.76‰ per °C (6.04/7.94)[10,15] in the Vostok sector, where a recent survey, however, provides an estimate ~15% higher[29]. We thus considered that $\delta^{18}O/T_s$ slopes are similar in each sector within estimated uncertainties (±10%). After correcting for the ocean isotopic change[30], $\Delta\delta^{18}O_{ocean}$, we used a common value of 0.8‰ per °C to infer ΔT_s. A small corrective term is then added to the Vostok ΔT_s in order to account for the upstream origin of the Vostok ice; this correction (maximum value of 1.2 °C at 330 kyr BP) is taken proportional to the distance upstream from Vostok. We then examined the possible influence of changes in oceanic sources combining information from both isotopes and inverting a simple isotopic model[10,19]. For the Vostok site[10], this method leads to $\Delta T_s = 0.176 \times \Delta\delta D + 0.501 \times \Delta d + 0.558 \times \Delta\delta^{18}O_{ocean}$ and we provisionally used the same formula for Dome Fuji. The comparison between the temperature records is essentially unaltered ($R^2 = 0.95$ instead of 0.96 for the curves displayed in Fig. 3a).

As a sensitivity test, we then applied the inversion formula derived for EPICA Dome C[19], $\Delta T_s = 0.161 \times \Delta\delta D + 0.446 \times \Delta d + 0.354 \times \Delta\delta^{18}O_{ocean}$, to both the Dome Fuji and Vostok records. This alternative approach leads to a similar conclusion ($R^2 = 0.96$). This temperature interpretation should nevertheless be considered preliminary until the inversion procedure has been applied to the Dome Fuji records. This might lead to a different $\delta^{18}O/T_s$ slope and reveal differences in the source correction between Vostok and Dome Fuji. However, although this would affect the ΔT_s amplitude it will not have a significant effect on the Dome Fuji/Vostok correlation.

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