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The transition from the last glacial period in inland and near-coastal Antarctica

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Abstract. Recent studies suggested that, during the transition out of the last glacial period, one near-coastal site in Antarctica showed a response similar to that of Greenland, and unlike that of central Antarctica. Here, we present a new high-resolution record of calcium from Dome C, Antarctica. Changes in flux of calcium, an indicator of dust input from other continents, should be synchronous across the region and probably the continent. Using Ca to synchronise records, we find that the main warming at the near-coastal site of Taylor Dome was slower than suggested previously, and similar to that of central Antarctica. Until there is further evidence, it is still a reasonable hypothesis that Antarctic climate behaved more or less as a single unit during the transition.

Introduction

One of the significant clues for understanding the causes and mechanisms of climate change during the last glacial cycle is the spatial pattern and temporal phasing of such changes. During the main transition from the last glacial maximum to the Holocene, central Antarctic ice cores show a different pattern to Greenland ice cores. In Greenland, the most prominent warming from the last glacial period is the rapid jump at about 14.8 kyr (calendar) into the Allerød/Bølling warm period [*Johnsen et al.*, 1992]. This was followed by a cooling during the Younger Dryas (YD), and a rapid final warming at about 11.7 kyr into the Pre Boreal. In cores from central Antarctica, most of the temperature increase occurs in a slow ramp from about 18.5 kyr, punctuated by a small cooling known as the Antarctic Cold Reversal (ACR) (e.g. [*Lorius et al.*, 1979]). Synchronisation of cores using methane records at Summit (Greenland), and Byrd and Vostok (Antarctica) has shown that the ACR began about 1000 years before the YD [*Sowers and Bender.*, 1995; *Blunier et al.*, 1997].

Recently, new records were published from an ice core at Taylor Dome (TD, Fig. 1), a near-coastal dome site in East Antarctica [*Steig et al.*, 1998]. Again, synchronisation was carried out using methane and oxygen isotopes in air. Based on the timescale adopted, it was suggested that, during the transition from the last glacial maximum to the Holocene, TD exhibits climate changes similar to those in Greenland (Fig. 2) [*Steig et al.*, 1998]. Specifically, TD appeared to show a fast warming rather than a slow ramp in temperature, and a reversal whose timing appeared to match the YD rather than the ACR.

Synchronisation using the Ca record

There is no doubt that climate can vary significantly over distances such as those between TD and Byrd or Vostok. However, some geochemical proxies should show a similarity across large regions. Here we present a calcium record from a new ice core drilled at Dome C, a central east Antarctic site (75°06'S, 123°24'E, Fig. 1). The core from Dome C was analysed in the field to a depth of 580 m, using continuous flow analytical methods for a range of chemistry, including Ca and Na [*Röthlisberger et al.*, 2000]. The data are available at high resolution, but in this paper are used generally as 1 m averages. A timescale has been prepared based on a number of criteria, mainly comparison of electrical horizons [*Wolff et al.*, 1999] and transitions with cores from nearby Vostok, and comparison of methane profiles with other well-dated records. However the arguments here do not rely on any absolute dating. Because the Dome C ice considered here is all in the top 15% of the ice sheet, nearly 3000 m above bedrock, thinning corrections are small. The non-sea-salt Ca record from Dome C (calculated with reference to Na) is presented in Fig. 2. In the Holocene part of the record, Ca is dominated by sea-salt (based on calculation from Na), but during the transition and the last glacial period, Ca is much elevated and originates from terrestrial dust. Ca at TD (also shown as non-sea-salt Ca in Fig. 2) also shows elevated concentrations in the glacial period [*Mayewski et al.*, 1996; *Steig et al.*, In Press].

Although modelling studies suggested that Australia may be a significant source of dust to Antarctica [*Genthon*, 1992], it has now been shown from geochemical studies that dust in both Dome C and Vostok cores in the last glacial period originates mainly from Patagonia [*Basile et al.*, 1997]. We therefore assume a Patagonian source, although our argument would still be valid if Australia were the source.

The TD and Dome C Ca records, in common with all other records of Ca or dust [*Petit et al.*, 1990] from Antarctica, show a major decrease between the last glacial period and the present-day. The magnitude of the decrease is rather similar (factor of 30 in concentration) at TD and Dome C. However, the time period over which the decrease occurs is quite different: the main decrease lasts around 1 kyr at TD, but about 3 – 4 kyr at Dome C; again we emphasise that, although the exact date of this decrease at Dome C is uncertain, the time period covered by it is rather insensitive to our assumptions.

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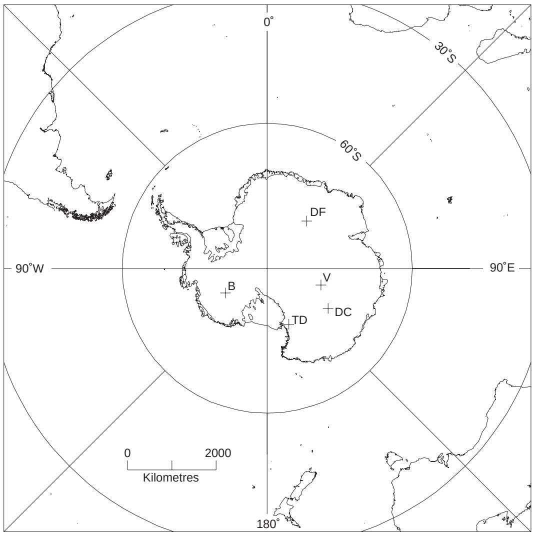

Figure 1. Location of ice core sites referred to in the text (B - Byrd, DC - Dome C, DF - Dome F, TD - Taylor Dome, V - Vostok) in relation to the Patagonian and Australian deserts, the possible long-range Ca source regions (Lambert azimuthal equal-area projection, scale true at centre).

We now consider the factors that can result in a change in terrestrial dust depositing to the snow in Antarctica. These are: (1) a change in the area, location, or aridity of the source, presumed to be in Patagonia; (2) a change in the uplift of dust from the source, due to changes in wind speed or other conditions at the source; (3) a change in efficiency or route of transport between the source and the ice core site; (4) a change in the loss of dust during the common oceanic transport route; (5) a change in local deposition efficiency in Antarctica.

In relation to Patagonia (or indeed Australia), TD and Dome C are very close, and we must assume they have the same Ca source. The only exception to this would be if very local sources were impacting TD in addition to the long-range sources affecting the whole region. However, in this case the flux of Ca at TD should have been considerably elevated over those at Dome C in the last glacial period, which seems not to be the case. It is obvious then that changes in factors (1) and (2) must impact TD and Dome C simultaneously. Similarly, in view of the closeness of TD and Dome C in relation to the transport route (involving at least a half rotation around Antarctica on average), changes in factor 3 and 4 must also give the same response at the two sites. Only the final factor can be significantly different at the two locations.

Dust is expected to be deposited mainly by dry deposition at sites with low snow accumulation rates (which is the case at Dome C where the modern accumulation rate is approximately 3 $g\,cm^{-2}\ a^{-1}$, and to a lesser extent TD where the accumulation is $5-7\,g\,cm^{-2}\,a^{-1}$ [*Morse et al.*, 1999]). In that case, concentrations will be altered by changes in snow accumulation rate. The change in accumulation rate between the glacial and Holocene periods in central East Antarctica was at most a factor 3 (e.g.[*Lorius et al.*, 1985]), and cannot explain the 30-fold change in Ca concentration seen. Changes in Ca flux at Dome C look very similar in shape to those in concentration. At TD, larger reductions in accumulation rate are suggested (based on the use of ^{10}Be concentrations) for the late glacial [*Steig et al.*, In Press], but not sufficient to explain the change in Ca concentration observed.

Thus, we find a clear result that the Ca concentration at Dome C reduces slowly over a period of several thousand years, during which TD apparently sees no change. TD concentration then reduces rapidly to levels comparable to those at Dome C. Such a scenario is not credible, and we suggest that the timescale at TD is in error in the period previously dated as 14.5 to 17.5 kyr, and the dating should be extended through this section by at least 2 kyr. As further backing for our belief that Ca should show similar trends across the region, Ca at Dome Fuji on the opposite side of the continent [*Watanabe et al.*, 1999] shows a similar decrease lasting several thousand years at the transition.

If the Ca record at TD is stretched to match more closely to Dome C, the effect is also to stretch the isotope (proxy temperature) record, such that the increase from the last glacial becomes a slow ramp that then looks like other Antarctic records, and unlike Greenland records. The stretching of the TD record that we propose in this part of the core requires that the layer thickness at TD for this section is very low. The most likely explanation for this would be greatly reduced accumulation rates. Although exceptionally low accumulation rates have been proposed [*Morse et al.*, 1998], we note that stretching the TD timescale further might be expected to lead to higher concentrations of ^{10}Be than were used to calculate the published timescale ([*Steig et al.*, 1998] – ^{10}Be is believed to have maintained a constant flux to the Antarctic ice sheet through the glacial stage, so any change in concentration observed in the ice implies a change in accumulation rate). We note that the radar internal layers [*Morse et al.*, 1998] show that this time period is thinner at the ice core location than at locations to the north and south. Because methane is rather invariant in the period 17 – 30 kyr, the gas matching (methane) provides little age control in this part of the ice [*Brook et al.*, 1999]. However, high methane concentrations consistent with air of age about 14 kyr are found in the upper part of the TD ice that has high Ca concentrations. This requires large differences between the gas-age and the ice-age which in turn requires very low accumulation rates as proposed.

The timing of the cold reversals

While we are confident about the Ca synchronisation at the termination of the glacial period and the results that flow from it, we are less confident about the more recent changes. There is little change in terrestrial Ca in the YD/ACR period. We do however note that the shape and magnitude of the Na signal at TD and at Dome C looks very similar, with a characteristic double peak during the period that is the ACR at Dome C, and that was identified as the YD at TD (Fig. 2). We have also noted a similar Na double peak in the Vostok ACR (V. Lipenkov, pers. comm.). We accept that there is less reason to expect synchroneity in the Na signals, with the possibility of local signals affecting the near-coastal site, but suggest that the similarity of shape and magnitude would nonetheless be surprising if these events were unrelated.

The dating through this section of the core [*Steig et al.*, 1998] is determined by calculation of the difference between the age of the ice and the age of the air (Δage). This is calcu-

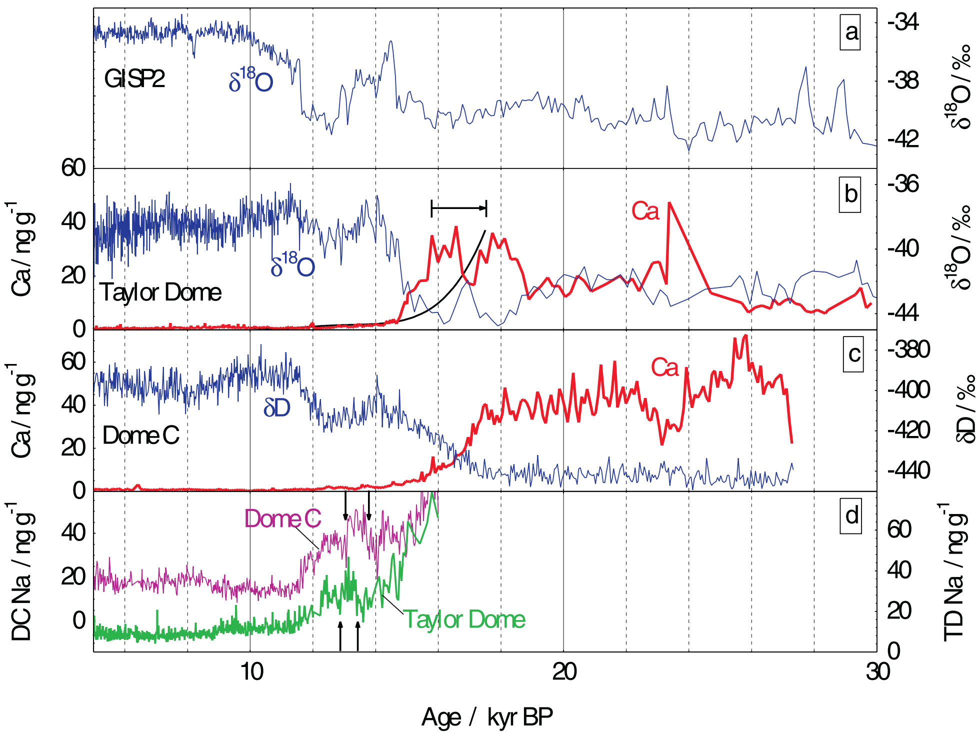

Figure 2. Comparison of records from GISP2, Taylor Dome and Dome C: a) GISP2 stable isotopes *Grootes et al.* [1993]; *Stuiver et al.* [1995]; b) Taylor Dome isotopes and non sea-salt Ca, with the estimated shape of the Ca profile through the termination of the glacial period assuming the same long range flux as seen in the Dome C Ca data - this curve can be interpreted as implying that the most recent high Ca value at 15.8 kyr could be re-dated as 17.5 kyr; c) Dome C isotopes and non sea-salt Ca; d) the Na records through the transition at Dome C and Taylor Dome, scales offset for clarity, arrows mark possible registration points at abrupt changes in Na levels. [In each record BP implies before 1950].

lated using the bubble close-off depth, the estimated surface temperature (using the isotope data), and the snow accumulation rate (estimated from ^{10}Be concentrations) [*Schwander et al.*, 1997]. In order to accommodate a change that would allow the Na profiles to match, the Δage would have to be increased by several hundred years.

Conclusions

While we cannot propose an absolute timescale, we find that the main transition in temperature probably has a similar span and shape (a slow ramp) at Dome C and Taylor Dome, and that, at least for this period, Antarctica can be considered to have experienced climate change as a block. This finding provides encouragement for theories of climate change that expect Antarctica to show a general out-of-phase response to the north during abrupt changes as a result of changes in ocean heat transport [*Stocker*, 1998]. Such models would have been severely tested by strong inhomogeneity within Antarctica. We suggest a new dating of the Taylor Dome Core should be constructed to accommodate both trace gases (CH_4, CO_2, $\delta^{18}O_{air}$ and $\delta^{15}N$) and Ca. We conclude that further clues should be sought through examining the strength of the out-of-phase response in the different near-coastal sectors of Antarctica, and through looking for the zones further north where a northern response changes to a southern response. Although further consideration is needed of the relative importance of source and transport effects, the Ca response in ice cores is likely mainly a result of changes in Patagonia and in the ocean zone south of Patagonia. This suggests that the "Antarctic response" applies also to southern Patagonia in some aspects of climate.

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