Holocene Climate Changes Recorded in an East Antarctica Ice Core

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Abstract

Ice core derived proxy climate records from Antarctica suggest that decadal, century and possibly even millennial-scale temperature variations in East and West Antarctica may be temporally asynchronous. For example, records from the Antarctic Peninsula indicate a strong 20th century warming in which the high plateau of East Antarctica has not participated. Similarly, a recent Neoglacial cooling, the "Little Ice Age", was prominent in East Antarctica, but absent in the Peninsula region. A new history of oxygen isotopic ratios ($\delta^{18}O$) and atmospheric dust concentrations from central East Antarctica suggests that the high inland plateau has been dominated by a cooling trend for the last 4000 years. Superimposed upon this isotopically-inferred cooling were a number of warmer events, the largest and most persistent of which occurred $\approx$ 3600 yr. BP and lasted several centuries. The most prominent event is a prolonged cold phase around 2200 yr. BP which is correlative with a mid-Neoglacial advance on South Georgia Island (Clapperton *et al.*, 1989). Most intriguing are several shorter-term (multi-centennial scale) $\delta^{18}O$ oscillations which are similar in magnitude to the glacial-interglacial transition in Antarctic ice cores. Although it is impossible to discount the effect of wind scouring and re-deposition in this low snow accumulation region, this 4000-year history raises important questions about the climate history on the high inland plateau during the last half of the Holocene. Certainly, a better spatial distribution of high resolution $\delta^{18}O$ records from East Antarctica are necessary to determine the extent to which the Plateau Remote record is spatially representative.

Introduction

Ice core histories with annual to centennial scale resolution are available from Antarctica depending upon the location of the core and the detail with which the core is analyzed. These cores provide "proxy" histories of atmospheric conditions such as condensation temperature, chemical composition, dustiness and volcanic disturbances. The history of net accumulation also may be determined when known time-stratigraphic horizons, such as annual layers, volcanic deposits, and radioactive horizons from thermonuclear testing can be identified. Mosley-Thompson *et al.* (1993) presented 500-year records of dust, $\delta^{18}O$, and net accumulation derived from a spectrum of cores from China, Greenland, Peru and Antarctica. Some proxies derived from ice cores reflect

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primarily local and/or regional conditions (e.g., accumulation) while others reflect more global-scale processes such as volcanism. Some proxies (e.g., $\delta^{18}O$ and dust) provide both regional and global-scale signals depending upon the characteristics of the site. For example, dust deposition on the Andean Altiplano reflects more localized processes while dust deposition in East Antarctica reflects hemispheric background levels.

The Plateau Remote Program

Environmental Setting

During December, 1986 and January 1987 two 200-metre cores were drilled at a remote site (84°S; 43°E; 3330 masl) near the Pole of Relative Inaccessibility on the East Antarctic Plateau (Fig. 1). These deeper cores were complemented by a number of 8 to 20-metre cores and the sampling of two pits. Weather conditions were generally clear with a persistent wind of 5 m s^{-1} from the quadrant between 320° and 10° (with reference to true north). Temperatures ranged from -26° to -40°C depending upon cloudiness and time of day.

Sastrugi as high as 0.4 to 0.5 metres were oriented along two prominent directions. The long axis of the first set of sastrugi was nearly parallel to the observed surface wind ($\approx$ 0° or true north) and to the surface contours (extracted from Drewey, 1983). The second set of sastrugi was oriented 30° to 40° from true north suggesting formation by wind obliquely crossing the elevation contours. This latter set of sastrugi may reflect the winter surface wind regime which exhibits high constancy due to the thermal wind effect which results when a extensive surface inversion layer lies over a gently sloping surface (Schwerdtfeger and Mahrt, 1968). The presence of sastrugi indicates the potential for stratigraphic disturbance by wind scouring and snow re-deposition which is discussed later in the paper.

Two previous studies of snow accumulation in this region were based upon snow pit stratigraphy and stake measurements. In 1966-67 Koerner (1971) investigated the stratigraphy of over 100 pits and measured accumulation on 99 stakes at Plateau Station (Fig. 1). His results indicate a mean accumulation of 28 mm ($\pm$4 mm) H_2O eq. and from a 10-metre pit he concluded that accumulation showed no long-term change over the last 127 years. Based upon his comparison of accumulation determined stratigraphically with that measured on stakes and determined from Beta radioactivity horizons, Koerner

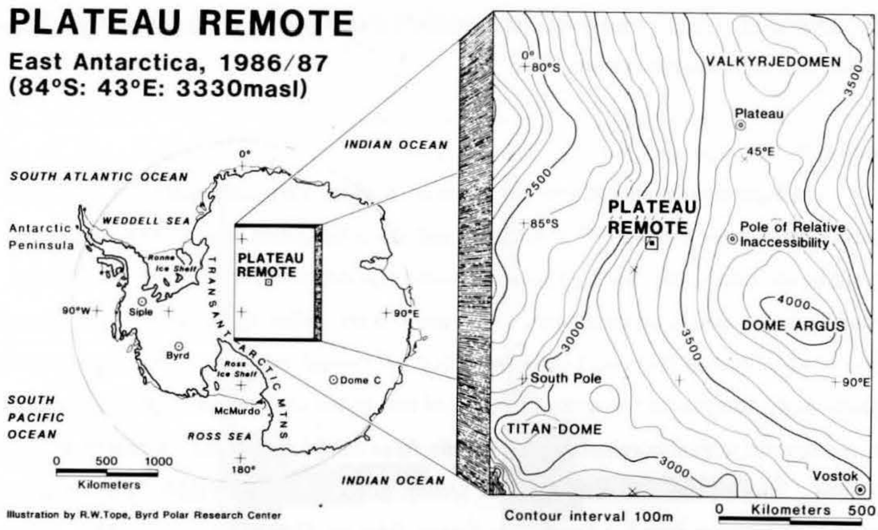

Figure 1: **The location of the Plateau Remote drill site is shown with respect to Vostok, Dome C, South Pole, Plateau Station and the Pole of Relative Inaccessibility.**

(1971) concluded that accumulation determined stratigraphically may be overestimated slightly. He suggested that 1 of 12 years at any site may be missing from the stratigraphic sequence. Leg One of the South Pole - Queen Maud Land Traverse (SPQMLT) left South Pole December 4, 1964 and arrived at the Pole of Relative Inaccessibility (Fig. 1) January 28, 1965 (Picciotto *et al.*, 1971). The traverse passed very close to the 1986/87 Plateau Remote drill site and based upon matching latitude, longitude and surface elevations, we have determined that SPQMLT Stations 24 and 25 bracket the Plateau Remote site. Accumulation ascertained from Beta radioactivity horizons range from 30 mm to 41 mm for Stations 24 and 25, respectively. Pit stratigraphy was observed only at Station 25, but indicated 50 to 58 mm of H_2O eq.

(Picciotto *et al.*, 1971), consistent with Koerner's observation that stratigraphic techniques tend to overestimate net accumulation

Dating the core

At Plateau Remote multiple sequences of samples were collected from two pits and density profiles were measured in both pits and along the entire length of both deep cores to aid in converting the firn thicknesses to water equivalent thicknesses. A preliminary estimate of net annual accumulation, based solely upon visible stratigraphy in the 2-metre pits, is 40 to 70 mm (H_2O eq.) with substantial interannual variability. Subsequent Beta radioactivity analyses of the upper 5 metres of two of the shallow cores (Fig. 2) indicate an average net annual accumulation of 42 mm from 1965 to 1986 and 33 mm from 1954 to 1964. This increase of $\approx$ 27% in net accumulation since 1965 (Table 1) is similar to the $\approx$20% increase found at South Pole Station (Mosley-Thompson *et al.*, 1995). The significance of this 'apparent' increase is difficult to assess from a few cores, particularly since net accumulation may be quite variable (spatially) in this region (Picciotto, 1971) and since 1 year in 12 may be missing from the stratigraphic sequence (Koerner, 1971).

A more rigorous estimate of annual net accumulation rate (A_n) is provided by identifying known volcanic eruptions with distinctive features. Excellent examples are two sets of double peaks or couplets in excess sulphate (EXS) which have been identified in cores from Antarctica and Greenland (see Fig. 10 in Mosley-Thompson *et al.*, 1993). Figure 3 illustrates these couplets. along with other volcanic deposits in the Siple Station and Plateau Remote records. The first couplet consists of an EXS peak deposited in 1810 by the 1809 eruption of an unidentified volcano (Dai *et al.*, 1991) while the peak deposited in 1816 originated from the 1815 eruption of Tàmbora. The second couplet reflects the eruption of Coseguina in 1835 and an unidentified eruption in 1828. Using the 1809 EXS peak in the Plateau core (Fig. 3) as a known time horizon gives an A_n estimate of 40 mm (H_2O eq.) from 1809 to 1986, or for the last 177 years.

Since annual chemical cycles and/or visible features, such as depth hoar layers, can't be identified at Plateau Remote due to the low accumulation rate, construction of the time scale requires making assumptions. First, the core was converted to water equivalent using the densities measured for each metre. The time scale was established by assuming a constant accumulation rate of 40 mm a^{-1}, the most robust estimate of A_n

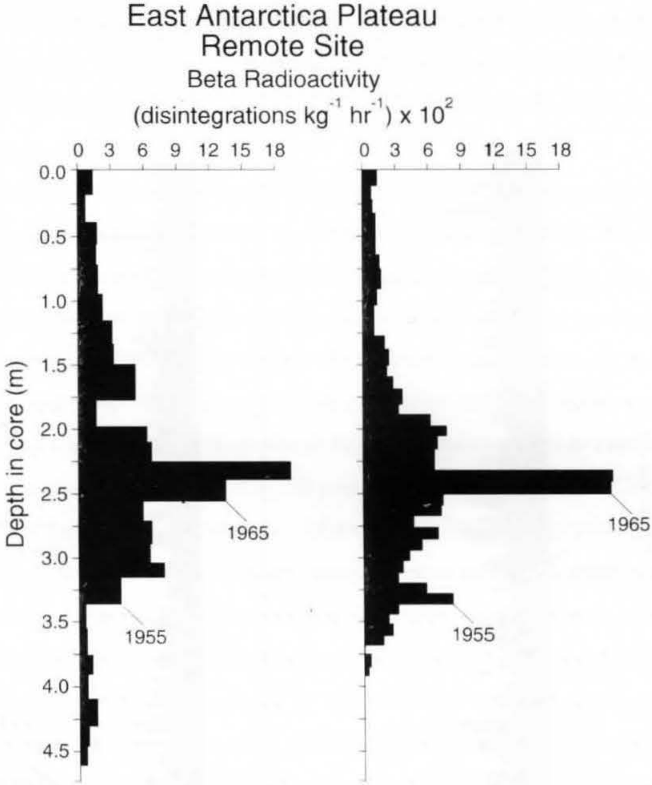

Figure 2: **Beta radioactivities are shown for two shallow cores drilled at Plateau Remote. The time stratigraphic horizons (1965 and 1955) are used to calculate the net annual accumulation averages (in mm H_2O eq.) given in Table 1.**

Table 1: **Average annual net accumulation(m H_2O equivalent) estimated at Plateau Remote and South Pole Station from identification of radioactive horizons deposited by thermonuclear bomb testing (see Figure 2).**

Beta Radioactivity Horizons	Plateau (2 cores)	South Pole (4 cores)
1965-1986	0.042	0.083
1954-1964	0.033	0.069
% Increase	27%	20%

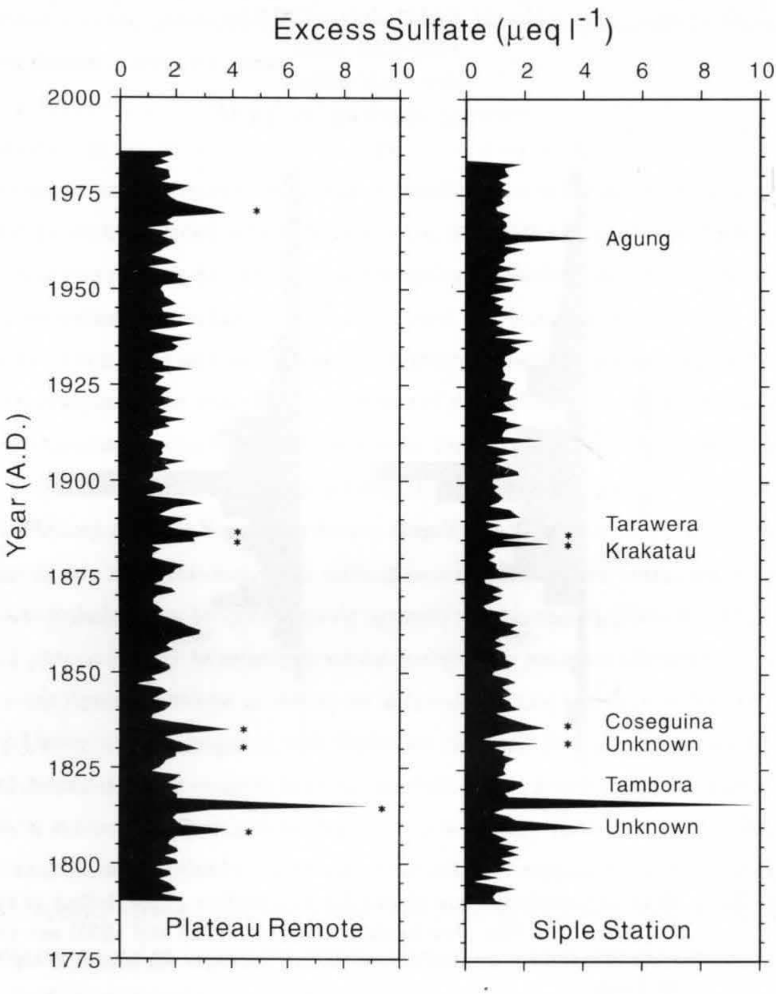

Figure 3: **Excess sulphate (μeq.l^{-1}) for the Plateau Remote core is plotted against that from the Siple Station ice core where the high accumulation permitted the counting of annual layers in $\delta^{18}O$ and SO_4^{-1} and the time scale is considered of excellent quality. Comparison of volcanic events in the Plateau Remote core with the correlative features in the well-dated Siple core provides an estimate of the net annual average accumulation at Plateau Remote.**

(discussed above) as it covers nearly two centuries. Since missing years are impossible to ascertain, no years were assumed to be missing. As discussed above, this is highly unlikely but it is impossible to know how many years are missing and where they are located in the stratigraphic sequence.

The potential time scale error can be estimated using several other time-stratigraphic features. Palais *et al.* (1987) identified a visible dust layer at 303.5 metres in a core from South Pole which was subsequently matched to a visible ash layer at Vostok. The age of this ash layer was estimated as ≈ 3200 yr. BP. In the Plateau Remote core a visible dust layer at 168 metres has been correlated tentatively to the South Pole ash layer. Based upon the simple time scale calculation discussed above (assuming A_n = 40 mm of H_2O eq. and no missing years) the age of the ash layer is calculated to be 3130 yr. BP which gives a difference of ≈ 70 years or a time scale error of 2.2% assuming that these features are correlative. Unfortunately, the ages of both the South Pole and Vostok ash layers are also estimates, hence there is no definite time-stratigraphic unit against which to calibrate the Plateau Remote time scale more precisely. Another major ash layer (not visible, but associated with elevated particulate concentrations, conductivity and excess sulphate) was found at 103.7 metres. The feature was verified by reproducing it in the second (parallel) core. The estimated time scale places this event at ≈ 290 A.D. If this event represents the 186 A.D. eruption of Taupo (New Zealand), currently a speculation, the time scale error would be ≈ 6.1%. At present the time scale inaccuracy is assumed to be ± 10%, which is excessive but safe. Future efforts will focus upon identification of other known volcanic events to constrain further the time scale of the 4000-year paleoclimate record obtained from the Plateau Remote core.

Integrity of the Data

As discussed above, low A_n precludes identification of annual variations in the chemical and physical parametres at Plateau Remote. To capture the decadal-scale variability, the entire core was cut into samples approximating the estimated annual layer thickness. A sample length of 50 mm was used from the surface to 29 metres where the sample size was reduced to 40 mm to adjust for densification. At 120 metres, the final transition from firn to ice, the sample size was reduced to 30 mm and held constant to the bottom of the core (203.8 m). A total of 5603 samples were analyzed for particulate concentrations and 3572 samples were analyzed for $\delta^{18}O$. All particulate analyses were conducted using a Model TA-II Coulter Counter under Class 100 Clean Room conditions at The Ohio State University. Samples were handled and cleaned in accordance with the protocols described elsewhere (Thompson, 1977; Mosley-Thompson and Thompson, 1982) which include continuous monitoring of the particulates in the Clean Room air and daily analysis of blank samples from the Milli-Q water system. The $\delta^{18}O$ analyses for the upper 75 metres were made at the Geophysical Institute of The University of Copenhagen and below 75 metres the $\delta^{18}O$ samples were analyzed using a Finnigan MAT Delta E mass spectrometer at The Ohio State University. The change in laboratories is transparent in the data and duplicate samples were checked by both laboratories. In addition, the core breaks were plotted along with the $\delta^{18}O$ data to ensure that no ^{18}O enrichment occurred at the ends of core pieces. No relationship between core breaks and enrichment exists. Core sections with unusually high or low $\delta^{18}O$ were first rerun by cutting fresh samples to check reproducibility and then were duplicated by analyzing correlative sections in the parallel core. In addition, vertical sequences of $\delta^{18}O$ samples collected from perpendicular walls of a 3-metre wide, 2-metre deep pit were analyzed and found to be reproducible (Fig. 4).

$\delta^{18}O$ and Dust Records From Plateau Remote

Figure 5 illustrates the $\approx$ 4000-year histories of insoluble dust concentrations (number of particles with diameters $\geq 0.63\ \mu m$) and $\delta^{18}O$ which are presented as un-weighted 10-year averages. Dust concentrations and $\delta^{18}O$ do not show strong co-variance on multi-decadal time scales. Sequences of decades with elevated dust deposition do not appear to be associated consistently with decades of snowfall either depleted (more negative) or enriched (less negative) in ^{18}O. Likewise, there is no indication of prolonged and enhanced dust deposition during the 'so-called' Little Ice Age as was reported from $\approx$ A.D. 1450 to 1850 in a core from South Pole Station (Mosley-Thompson and Thompson, 1982).

The Plateau Remote core provides the longest high-resolution dust history for the East Antarctic Plateau and reveals multi-century long trends in the background dust concentrations, upon which shorter-term (multi-decadal) dust peaks are superimposed. For example, dust concentrations were consistently high from 4000 to 3500 yr. BP, but around 3500 yr. BP concentrations dropped abruptly and remained lower until $\approx$ 2500 yr. BP. From 2500 yr. BP to $\approx$ 1700 yr. BP concentrations increased gradually

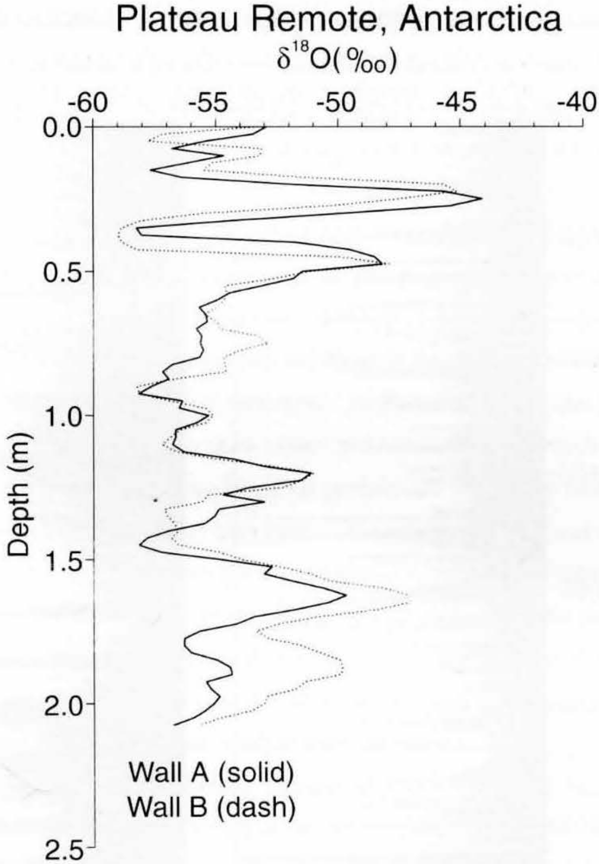

Figure 4: **Two vertical $\delta^{18}O$ profiles collected 3 metres apart on perpendicular pit walls demonstrate the reproducibility of the $\delta^{18}O$ signal preserved at Plateau Remote.**

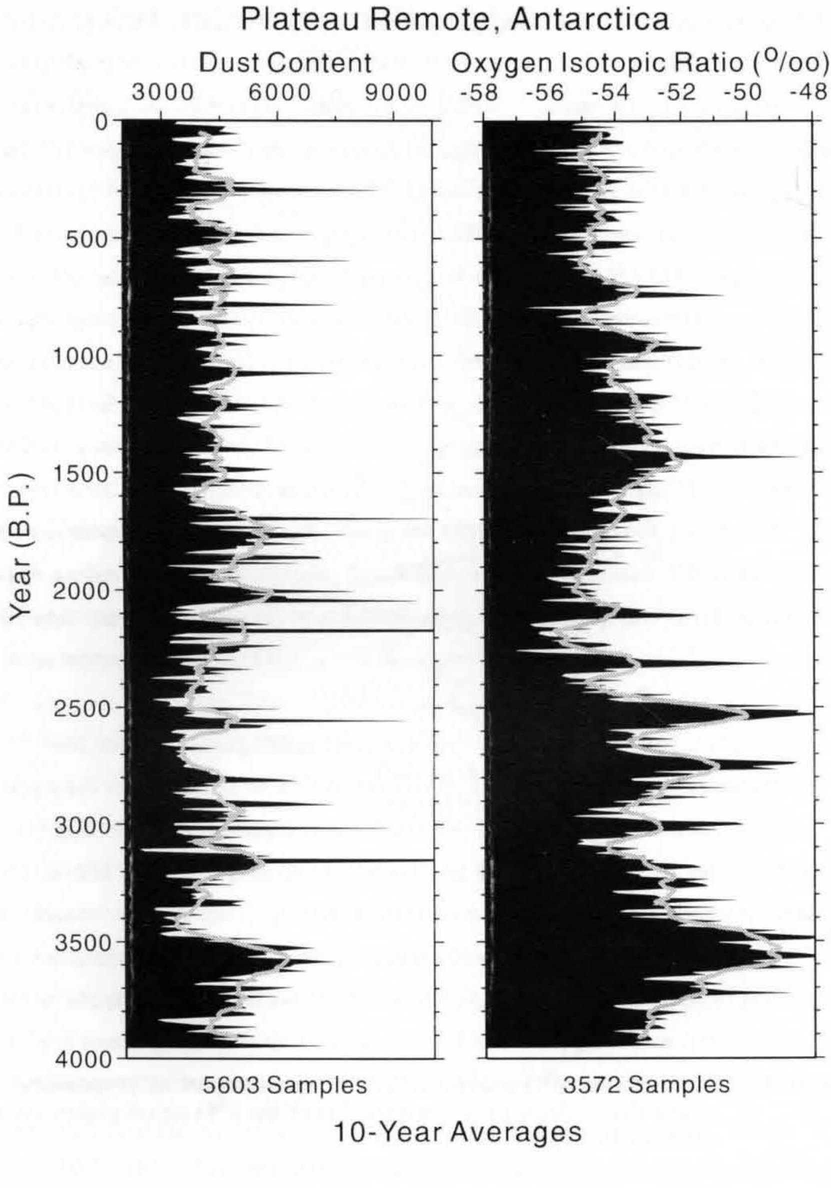

Figure 5: **Decadal averages of the dust concentrations (diameters ≥ 0.63μm) per ml sample and $\delta^{18}O$ at Plateau Remote suggest no consistent relationship between elevated atmospheric dustiness and cooler conditions during the last 4000 years. The solid line is the 100-year unweighted running mean and the number of samples upon which each record is based is shown at the bottom.**

reaching concentrations nearly equivalent to those at 3600 yr. BP. Since 1600 yr. BP concentrations have remained fairly constant at levels similar to those from 3500 to 2500 yr. BP. Superimposed upon the 4000-year dust history are century-long intervals of dustiness (e.g., $\approx$ 3150 yr. BP), as well as sporadic events lasting only a few decades (e.g., 2900 and 1500 yr. BP).

Hogan (1975) pointed out that the remote East Antarctica Ice Sheet should be an ideal site for investigating temporal variations in the global (or at least hemispheric) particulate mass as there are few local sources. However, Junge (1977) noted that the relationship between atmospheric particulates and those in the resulting precipitation is neither direct nor simple and is poorly understood. At Plateau Remote, like South Pole, most of the snow arrives as clear sky snow crystal precipitation within which insoluble dust particles serve as condensation nuclei. Dust particles are also swept from the atmosphere by the falling crystals and snowflakes. The relative roles of wet and dry deposition remain unquantified, but on glacial-interglacial time scales periods of reduced accumulation have been shown to be characterized by increased particulate deposition (Lorius *et al.*, 1985), suggesting that dry deposition is not negligible. At Plateau Remote the lack of annual layers and known time horizons makes it impossible to examine the relationship between elevated dust and reduced snow accumulation.

Figure 5 also illustrates the 10-year averages of $\delta^{18}O$ which range from a low of $\approx$ -57.3 ‰ around 2200 yr. BP to a high of $\approx$ -47.5 ‰ at 3500 yr. BP. For comparison, the 20th century average is -54.6 ‰. Like the dust record, $\delta^{18}O$ also exhibits variations on decadal to centennial time scales. Figure 5 reveals a number of large and relatively-abrupt isotopic excursions lasting from a few decades to a few centuries with some of them (e.g., 3000, 2800 and 2500 yr. BP) clearly approaching magnitudes equal to that of the Holocene/Late Glacial Stage (LGS) transition (5 to 6 ‰). Those $\delta^{18}O$ fluctuations lasting a few decades to a century probably reflect a combination of changes in the seasonal distribution of precipitation, snow deposition, deflation at the drill site, and/ or some short-term change in the moisture source region.

The issue of the relationship between signal and noise in the $\delta^{18}O$ record from East Antarctica where accumulation is low is worth elaboration and has been addressed by Ciais *et al.* (1994). For their interpretation of the Vostok Holocene record Ciais *et al.* (1994) adopted a 500-year cut off, corresponding to a signal to noise ratio of 4 to 1. Their $\delta^{18}O$ analyses were for samples containing $\approx$ 50 years each which were cut of equal size throughout the Holocene part of the core. In contrast, the size of the Plateau Remote samples was reduced with depth and contain 1 to 3 years per sample so that the signal to noise cut off should be substantially less than 500 years. Although $\delta^{18}O$ excursions lasting less than 100 years may be dominated by surface processes, it is unlikely that multi-centennial events are artifacts of scouring and re-deposition. The question of their spatial representivity remains and may only be addressed by future high resolution $\delta^{18}O$ analyses of other East Antarctica ice cores.

Although these abrupt and brief isotopically warm excursions are not unlike those found between 60,000 to 20,000 years ago in cores from central Greenland (Kerr, 1993; see his figure), they are different in several ways. First, the isotopic excursions at Plateau Remote are not associated with changes in the dust flux as they are in Greenland and similar excursions have not been reported elsewhere in Antarctica. Central East Antarctica is generally thought to be buffered from abrupt changes, yet the Plateau Remote isotopic record suggests multi-century-long changes in atmospheric temperatures, atmospheric circulation patterns around the continent, moisture source regions, or some combination of these factors. The moisture source region for the central East Antarctica Plateau is thought to be the sub-tropics (Koster *et al.*, 1992) and if true, changes in the moisture source should be evident in future high resolution $\delta^{18}O$ records from the Plateau.

Of more significance are the longer time scale $\delta^{18}O$ changes. Figure 6 illustrates the 100-year running mean of $\delta^{18}O$ with a long-term linear trend superimposed. A number of alternating warmer and cooler phases, lasting from several to seven centuries are superimposed upon the cooling trend ($\delta^{18}O$ depletion of $\approx 3^{o}/_{oo}$). Around 2500 yr. BP $\delta^{18}O$ drops from -50 $^{o}/_{oo}$ to a low of nearly -56 $^{o}/_{oo}$ 400 years later. For reference, the Holocene/LGS $\delta^{18}O$ transition is 5.7 $^{o}/_{oo}$ at Vostok and 5 $^{o}/_{oo}$ at Dome C (Lorius *et al.*, 1985). If depositional effects are not responsible for these $\delta^{18}O$ variations, then they must reflect variable atmospheric conditions during the last half of the Holocene. These results challenge the currently held concept of a 'stable' Holocene climate, but await confirmation from additional high resolution $\delta^{18}O$ histories from East Antarctica.

The only other isotopic histories ($\delta^{18}O$ or δD) available from East Antarctica for comparison with the Plateau Remote record are not based upon continuous analyses or comparably small sample sizes. Ciais *et al.* (1992) composited cores from Vostok, Dome C, and Komsomolskaia in East Antarctica and reported evidence of a continent-wide early Holocene climatic optimum (6,500 to 10,000 yr. BP). These records were filtered to

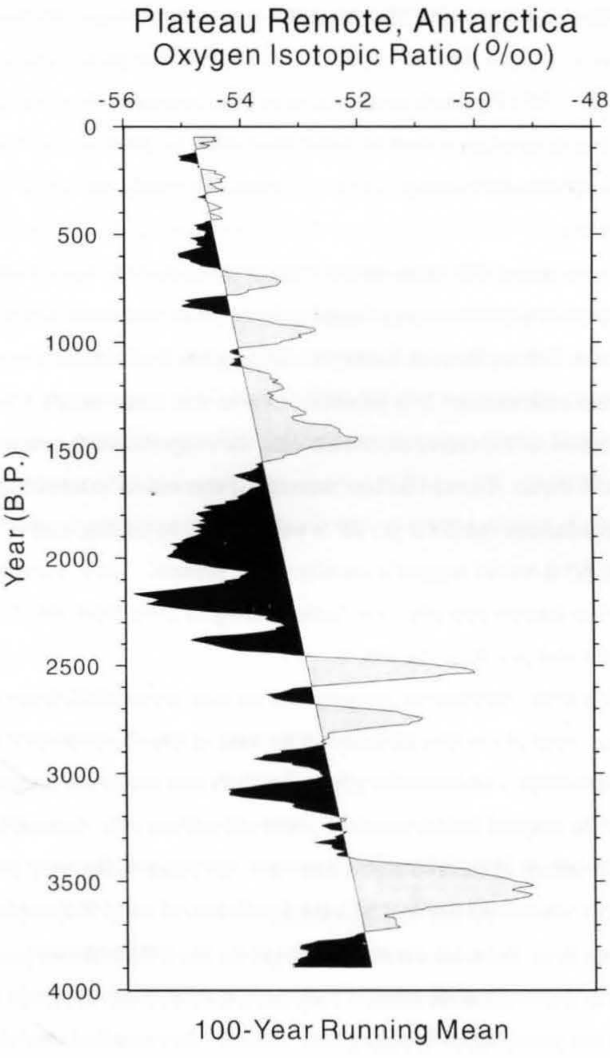

Figure 6: **The 100-year running mean for the 4000-year record of $\delta^{18}O$ suggests a long-term cooling trend with large and abrupt isotopic oscillations superimposed. Note that the linear trend is influenced by the 'warm' event near the end of the record. Interpreting $\delta^{18}O$ using the classical paleoclimatic isotope-temperature relationship suggests tha last half of the Holocene over the central East Antarctica Plateau was variable with multi-century long warmer and cooler events. The most prominent feature is the Holocene Neoglacial event ($\approx$2500-1600 yr. BP).**

remove variations on time scales less than 500 years which makes comparison with the last 500 years at Plateau Remote impossible. However, the prominent cool event from 2500 to 1600 yr. BP (Fig. 6) is evident also in their composite (see Ciais *et al.*, 1992; Fig. 5) which also displays a cooling trend from 4000 to 2000 yr. BP followed by a warming and subsequent cooling, which are similar in trend, but not in magnitude, to those in Figure 6.

The most recent 500 years of the Ciais *et al.* composite record reflects the smoothing function which removes frequencies less than 500 years and thus can not be compared to the Plateau Remote history which suggests a continued cooling trend during the most recent millennium. It is important to note that linear trends fitted to climate data are quite sensitive to the nature of climate near the endpoints of the record. The cooling trend shown in Figure 6 would be less dramatic if this record extended only to 3000 yr. BP. If it extended only to 2000 yr. BP it would show no cooling and if it extended to only 1000 yr.BP it would suggest a cooling to the present. Thus, trends should be viewed over the longest possible time frame bearing in mind their sensitivity to extreme values near the end points of the record.

Finally, it is important to consider that the long-term (4000-year) trend in isotopic depletion (Fig. 6) might reflect partially an increase in the elevation of the ice sheet due to snow accumulation. Unfortunately, past ice sheet elevations are virtually impossible to determine as the trapped bubble pressures have not proven very successful as a proxy and the upper 120 metres of the 200-metre core have not experienced pore close-off (that is, the core is still considered firn to 120 metres). Lorius *et al.* (1984) explored the potential effect of the LGS to Holocene elevation changes on the $\delta^{18}O$ histories preserved in the Byrd, Dome C and Vostok ice cores. They concluded that the influence of the altitude of formation of the precipitation is negligible. Further, they reported that the Vostok gas results are consistent with the interpretation of borehole temperatures by Ritz *et al.* (1982) and that both of these suggest a 'slight' thickening of the central part of East Antarctica since the end of the LGS. A recent paper by Martinerie *et al.* (1994) suggests that air content in the Vostok core may reflect a combination of changes in ice sheet elevation, atmospheric pressure and the influence of the wind on the ice porous volume. They suggest that changes in wind strength might contribute to the large variations in air content at Vostok during the LGS. It is unlikely that ice sheet elevation changes over the last 4000 years would be sufficient to account for the decreasing $\delta^{18}O$ trend of 2 to 3 $^{o}/_{oo}$

and elevation would not change quickly enough to produce the large $\delta^{18}O$ fluctuations observed over multiple centuries.

Using for Plateau Remote the same $\delta^{18}O$ - temperature relationship (0.8 ‰ per 1°C) used for climatic interpretation of the Vostok $\delta^{18}O$ record (Lorius *et al.*, 1984), gives a 2.5 to 3.7°C cooling trend over central East Antarctica from 4000 yr. BP to the present. This cooling, if real, is inconsistent with other Holocene $\delta^{18}O$ records from Antarctica and begs the question of whether the climatic interpretation of $\delta^{18}O$ is correct. Some support for this Holocene cooling trend is found in the recently published $\delta^{18}O$ record from Huascarán in northern Peru which shows a 2.5 ‰ depletion (cooling) from 4000 to 200 yr. BP (Thompson *et al.*, 1995) . With the exception of the marked warming of the last two centuries, the $\delta^{18}O$ inferred temperatures in the Peruvian highlands have cooled since the Holocene maximum at 6500 yr. BP. This is particularly interesting as the tropical and sub-tropical Atlantic waters are the source of the Huascarán moisture.

Conclusions

These Plateau Remote $\delta^{18}O$ and dust histories are unparalleled in East Antarctica for their temporal resolution and they raise interesting questions about mid to late Holocene climate conditions over East Antarctica. In summary, late Holocene cool phases do not appear to be associated with increased concentrations of atmospheric dust as was the case during the LGS and climatic conditions inferred from $\delta^{18}O$ appear to have alternated between warmer to cooler conditions on time scales of a few centuries. The isotopic differences between these warm and cool phases are large, in some cases nearly comparable to the Holocene/LGS differences found in cores from Vostok and Dome C. The spatial extent of these fluctuations must be explored by the $\delta^{18}O$ analysis of other cores.

The most prominent feature in the Plateau Remote record is the prolonged cool phase from 2500 to 1600 yr. BP, with the coldest conditions around 2200 yr. BP. This cold period is correlative with a mid-Neoglacial glacial readvance on South Georgia Island dated around 2200 yr. BP by Clapperton *et al.* (1989). Although Clapperton *et al.* (1989) also identify a "Little Ice Age" readvance, it is much less prominent than the mid-Neoglacial ($\approx$ 2200 yr. BP) readvance. Finally, the 4000-year $\delta^{18}O$ record exhibits a long-term trend of ^{18}O depletion (2 to 3 ‰), which may reflect a cooling of 2.5 to 3.7°C.

Whether these dust and $\delta^{18}O$ records are representative of the high East Antarctica Plateau must be confirmed or refuted by additional East Antarctica ice core histories with equivalent temporal resolution. The upcoming European Ice Coring Program in Antarctica (EPICA) will retrieve a core to bedrock in East Antarctica which should make it possible to investigate further the rapid and large Holocene changes suggested by the Plateau Remote ice core record. Comparable high resolution records for the high, inland region of West Antarctica are scanty and will be obtained in the near future by the West Antarctica Ice Sheet Program (WAIS) proposed by U.S. scientists.

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References

Ciais P, Jouzel J, Petit JR, Lipenkov V, White JWC. (1994) Holocene temperature variations inferred from six Antarctic ice cores. Annals of Glaciology, 20, 427-439

Ciais P, Petit JR, Jouzel J, Lorius C, Barkov NE, Lipenkov V, Nicolaiev V (1992) Evidence for an early Holocene climatic optimum in the Antarctic deep ice-core record. Climate Dynamics, 6, 169-177

Clapperton CM, Sugden DE, Birnie J, Wilson MJ (1989) Late-glacial and Holocene glacier fluctuations and environmental change on South Georgia, Southern Ocean. Quaternary Research, 31, 210-228

Dai J, Mosley-Thompson E, Thompson LG (1991) Ice core evidence for an explosive tropical volcanic eruption 6 years preceding Tambora. Journal of Geophysical Research, 96, 17, 361-117, 366

Drewry DJ (1983) Antarctica: Glaciological and Geophysical Folio. Scott Polar Research Institute (U. of Cambridge), England

Hogan AW (1975) Antarctic aerosols. Journal of Applied Meteorology, 14, 550-559

Junge CE (1977) Processes responsible for the trace content in precipitation. In: Isotopes and Impurities in Snow and Ice. IAHS-AISH Publication 118, 63-77

Kerr RA (1993) Even warm climates get the shivers. Science, 261, 292

Koerner RM (1971) A stratigraphic method of determining the snow accumulation rate at Plateau Station, Antarctica, and the application to South Pole - Queen Maud Land Traverse 2, 1965-1966. In: Antarctic Snow and Ice Studies, II (Ed. A.P. Crary), American Geophysical Union, 225-238

Koster RD, Jouzel J, Suozzo RJ, Russell GL (1992) Origin of July Antarctic precipitation and its influence on deuterium content: a GCM analysis. Climate Dynamics, 7, 195-203

Lorius C, Raynaud D, Petit JR, Jouzel J, Merlivat L (1984) Late-glacial maximum-Holocene atmospheric and ice-thickness changes from antarctic ice-core studies. Annals of Glaciology, 5, 88-94

Lorius C, Jouzel J, Ritz C, Merlivat L, Barkov NI, Korotkevitch YS, Kotylavok VM (1985) A 150,000-year climatic record from Antarctic ice. Nature, 316, 591-596

Martinerie P, Lipenkov VY, Raynaud D, Chappellaz J, Barkov NI, Lorius C (1994) Air content paleo record in the Vostok ice core (Antarctica): A mixed record of climatic and glaciological processes. Journal of Geophysical Research, 99, 10565-10576

Mosley-Thompson E, Thompson LG (1982) Nine centuries of microparticle deposition at the South Pole. Quaternary Research, 17, 1-13

Mosley-Thompson E, Thompson LG, Dai J, Davis ME, Lin PN (1993) Climate of the last 500 years: high resolution ice core records. Quaternary Science Review, 12, 419-430

Mosley-Thompson E, Thompson LG, Paskievitch JF, Pourchet M, Gow AJ, Davis ME, Kleinman J. (1995) South Pole snow accumulation has increased in recent decades. Annals of Glaciology, 21, in press

Palais JM, Kyle PR, Mosley-Thompson E, Thomas E (1987) Correlation of a 3,200 year old tephra in ice cores from Vostok and South Pole Stations, Antarctica. Geophysical Research Letters, 14, 804-807

Picciotto E, Crozaz G, DeBreuck W (1971) Accumulation on the South Pole - Queen Maud Land traverse, 1964-1968. In: Antarctic Snow and Ice Studies, II (Ed. A.P. Crary), American Geophysical Union, 257-315

Ritz C, Lliboutry L, Rado C (1982) Analysis of a 870 m deep temperature profile at Dome C. Annals of Glaciology, 3, 284-289

Schwerdtfeger W, Mahrt LJ (1968) The relation between the Antarctic temperatureinversion in the surface layer and its wind regime. IASGE Symposium, Hanover, NH, p. 308-315

Thompson LG (1977) Microparticles, ice sheets and climate. The Ohio State University Institute of Polar Studies (Columbus, Ohio, Report 64)

Thompson LG, Mosley-Thompson E, Davis ME, Lin P-N, Henderson KA, Cole-Dai J, Bolzan JF, Liu K-b (1995) Late Glacial Stage and Holocene tropical ice core records from Huascarán, Peru. Science, 269, 46-50