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ISOTOPE CLIMATIC RECORD OVER THE LAST 2.5 KA FROM DOME C, ANTARCTICA, ICE CORES

by

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ABSTRACT

Data on climatic changes over thousands of years is needed for a better understanding of the shorter term variations which are of interest to man. For this purpose we measured the isotope composition (δDo/oo) of two adjacent ice cores drilled in the Dome C area. The time scale was established using the remarkably constant mean annual accumulation rate (37 kg m^{-2}) determined by various techniques. The detailed isotope records were smoothed to filter out the δ value fluctuations not directly related to local temperature changes. With respect to conditions over the last 2.5 ka, the combined smoothed δ curve indicates a cooler climate from about 1800 to 1200 AD and a slightly warmer period from about 1200 to 700 AD. These periods may well correspond to the suggested world-wide Little Ice Age and medieval warm phase. Using the present δDo/oo/T°C measured at the surface, the maximum amplitude for these two periods, after smoothing with a low pass filter of 512 a, is approximately -0.35 and +0.3°C, respectively.

INTRODUCTION

Climatic changes over decades or centuries are of particular importance to man. To put present changes in a proper perspective, information on a much longer time scale is required, typically of the order of 1 ka. Furthermore, the changes are not necessarily synchronous for different locations nor uniform in amplitude, nor even in direction, and improved knowledge and understanding of climatic variations over this time interval, therefore, requires a global data base with sufficient regional resolution. Although some instrumental and proxy data are available, they come mainly from the northern continental areas, leaving a real need for data from high southern latitudes, i.e. from Antarctica. As the instrumental record on this continent does not go beyond the last 25 a, a tentative evaluation of longer term climatic changes over several thousand-year periods may be obtained from the isotopic (δ) composition of successive snow layers.

Many factors other than the atmospheric condensation temperature may influence the mean δ composition of the deposited cold snow layers, such as the isotopic composition and temperature of the oceanic source, the condensation and evaporation processes in the atmosphere, the seasonal distribution of accumulation, and in situ diffusion processes (Dansgaard and others 1973). These factors, which are not directly related to local temperature fluctuations, cause a "noise" in the isotope-temperature record and a detailed study from adjacent ice cores in Greenland has shown the particular importance of local areal inequalities in snow deposition (Reeh and Fisher to be published*). The validity of the δ climatic record has been evaluated by various means (comparison of seasonal and annual δ and atmospheric temperatures on both temporal and spatial scales and interpretation of in situ depth-temperature profiles taking into account past surface temperature changes derived from the isotopic record) summarized by Robin (1981 and in press). The overall conclusion is that similar trends of isotopes and temperature do exist over wide areas, the relationship becoming better as the period over which data are averaged is

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increased. This conclusion applies in particular to the interior of the Antarctic ice sheet. The isotopic model of Jouzel and Merlivat (unpublished*) further supports the validity of the δ record as a climatic indicator. It should be kept in mind that difficulties in the interpretation of the isotope climatic record may also arise from the flow, deformation, and changing size and thickness of the ice sheet. These factors can, however, be neglected when considering time series over one- or several thousand-year periods obtained from central areas where the ice thickness is very large and the ice accumulation and flow very low.

In this paper, we present the δ time series from two adjacent ice cores from Dome C (74°39'S, 124°10'E; elevation 3 240 m; present mean annual temperature -53.5°C) obtained during the 1977-78 and 1979-80 Antarctic field seasons as part of the International Antarctic Glaciological Project. Using an empirical approach, an attempt will be made to use these results to describe the climatic changes which occurred over the last 2.5 ka in this area.

ISOTOPE MEASUREMENTS

The deuterium values were determined by mass spectrometry and are expressed in δD°/oo vs standard mean ocean water (SMOW) with a D/H ratio equal to 155.76×10^{-6}; the accuracy of the measurements (one standard deviation) is ±0.5°/oo.

THE DEPTH SCALE

Discontinuous density ρ measurements have been approximated (Fig.1) by a continuous ρ-depth profile showing a linear increase from 0 to 20 m (ρ = 550 kg m^{-3}) followed by a power law up to the close-off density. The measured and calculated densities agree quite well with those from the model proposed by Herron and Langway (1980); the curve shown in Figure 1 will be used to present the δ profile in metres of ice equivalent.

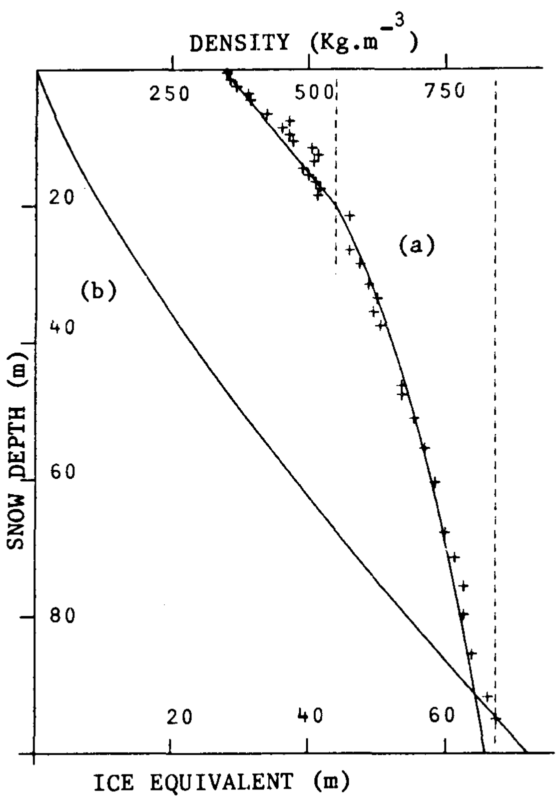

Fig.1. Line (a) represents measured and calculated density at Dome C plotted against depth, and line (b) is the equivalent depth in metres of ice.

*Jouzel J, Merlivat L Unpublished. Deuterium and oxygen 18 in precipitation. A global model from the oceans to the ice caps.

THE TIME SCALE

The depths of the 1955 and 1965 radioactive fallout layers were determined by laboratory measurements on a series (about 20) of shallow cores (Petit and others in press) and, in the field, by in situ γ-ray measurements (Pinglot and Pourchet 1981). The resulting mean annual accumulation rate for a 20 km^2 area over approximately the last 25 a is 32±1 kg m^{-2}. Stratigraphic studies and ^{210}Pb determinations (Petit and others in press) give slightly higher values, respectively 37 (with unlikely extreme values of 44 and 33) and 36±5 kg m^{-2} a^{-1} over the last 100 a. The 100 a time scale obtained using a value of 37 kg m^{-2} a^{-1} has been checked using the peaks in the sulphate concentration profile corresponding to major southern hemisphere volcanic eruptions, in particular Krakatoa in 1883 and Agung in 1963 (Delmas and Boutron 1980); these volcanic events were also detected by conductivity measurements (Legrand 1980). A value of 37 kg m^{-2} a^{-1} can thus be taken for the mean accumulation rate over the last 100 a. When extrapolated to greater depths, the chronology obtained agrees within a few per cent with the suggested interpretation of the peaks observed for sulphate concentration, static electrical conductivity (Maccagnan and others 1981), and microparticle concentration (A Royer personal communication) at about 104.5 m depth, which links them with the Taupo, New Zealand, volcanic eruption of 186 AD (Wilson and Walker 1980). This suggests that the snow accumulation rate in the Dome C area has been relatively

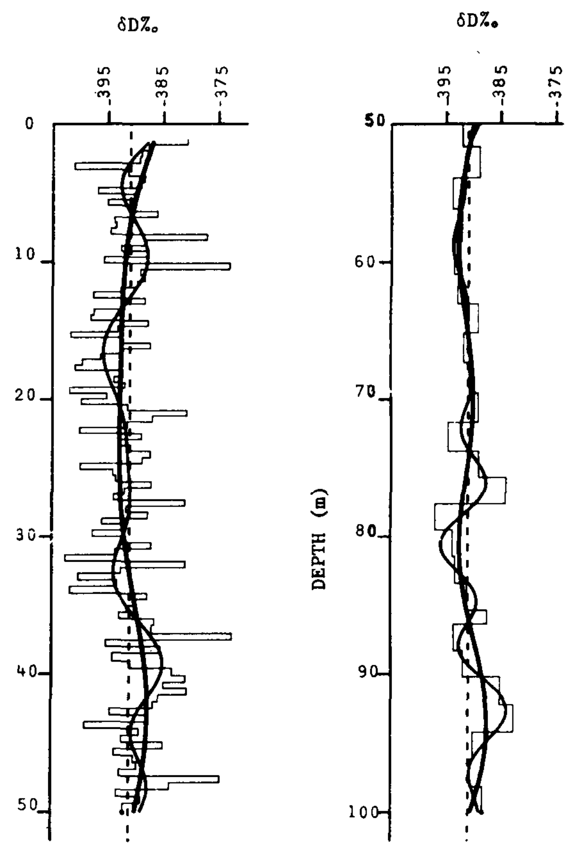

Fig.2. δD°/oo profile over the first 100 m from the 1978 Dome C ice core. The smoothed curves have been obtained using 170 and 512 a filters. The dotted line indicates the mean value.

constant over almost the last 2 ka. The mean accumulation rate of 37 kg m^{-2} a^{-1} (corresponding to 40 mm of ice equivalent) was then used to obtain a time scale for the δ time series presented below. It should also be pointed out that this value is in good agreement with short-term microparticle concentration changes (assuming they reflect seasonal changes) which were used over the same depth scale to determine discontinuous annual accumulation values (Thompson and others 1981). The chosen surface reference level for both ice cores corresponds to January 1978.

ISOTOPE PROFILE FROM THE 906 m DEEP ICE CORE

The $\delta^{18}O$°/oo profile averaged for samples with lengths of about 4 m has been used to describe climatic changes over the last 30 ka (Lorius and others 1979). In addition, the upper part of the ice core obtained during the 1977-78 field season (Lorius and Donnou 1978) has also been analysed using successive 0.66 m long increments down to a depth of 74 m and 2.55 m increments further down. The δD°/oo profile covering the upper 100 m is given in Figure 2.

A crude test using Gaussian paper indicated that the data come from a Gaussian population and have no linear trend. The weighted mean is m_1 = -390.9 δD°/oo and the standard deviation σ_1 = 4.7 δ°/oo down to a depth of 105.5 m of ice.

ISOTOPE PROFILE FROM THE 180 m DEEP ICE CORE

An adjacent ice core was obtained during the 1978-79 field season, about 10 m away from the first (Gillet and Rado 1980). The results of the detailed (0.1 m long continuous increments) δD°/oo measurements down to a depth of 100 m are shown in Figure 3. Results are available down to 136 m of snow. The same test shows again that the data come from a Gaussian population with m_2 = -391.0 δD°/oo and σ_2 = 8.9 δD°/oo.

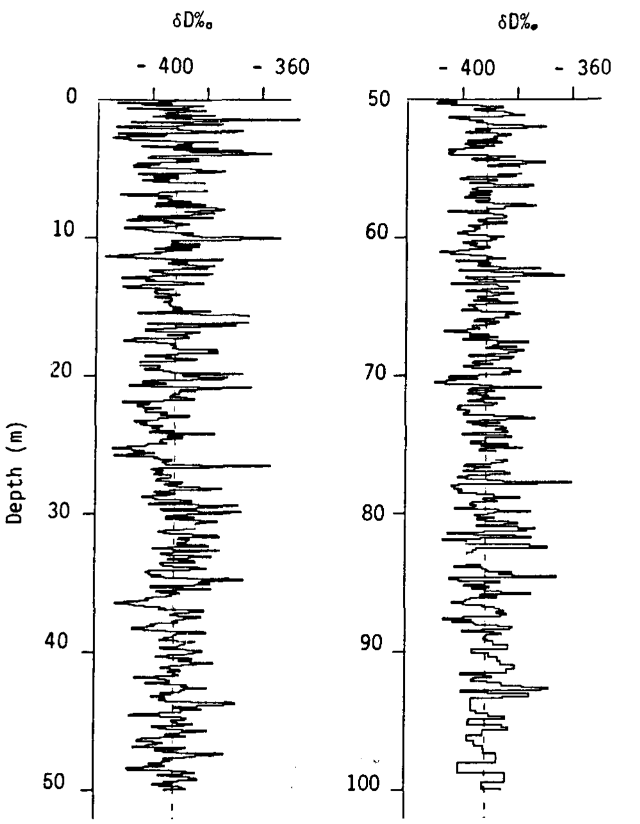

Fig.3. δD°/oo profile over the first 100 m from the 1979 Dome C ice core. The dotted line indicates the mean value.

VARIABILITY OF THE ISOTOPIC SIGNAL

Before comparing results from the two ice cores, the variability of the deuterium signal should be discussed for different time scales. This can be done using available spatial and temporal data.

The basic features of the snow accumulation pattern in the Dome C area are well documented. Petit and others (in press) showed that the removal process at the surface can lead to the absence of accumulation at a given point over significant time periods, resulting in the disappearance of isotopic seasonal indexes. This process therefore introduces noise in the δ record. The noise can be estimated from the spatial variability of the mean δ value registered in firn cores covering the same period. The spatial variability was determined experimentally from 20 snow cores, each representing an accumulation of 13 to 15 a, which show a variability (1 σ) of 6°/oo in δD (Petit and others in press).

In addition, the 180 m ice-core data were regrouped to obtain sampling conditions comparable to those of the 1979 core. The standard deviations calculated for both profiles over a depth of 50 m (ice equivalent) are identical, with a value of σ = 6.5°/oo for increments representing snow accumulation of about 10 a. These values are identical with the value obtained above from spatial observations.

A more complete discussion, taking into account the natural in situ δ signal smoothing, will be published elsewhere. It is sufficient to indicate here that the variability of the δ profiles can be explained mainly by irregularities due to snow accumulation, which disturb the original isotopic precipitation signal.

This noise component decreases as $\sqrt{n}$ (Robin 1981) and can thus be expressed in the Dome C area from our experimental results by $23/\sqrt{n}$, n being the number of years. This noise is higher than in other stations (Robin in press), where the snow accumulation rates are greater.

COMPARISON OF THE TWO ISOTOPE PROFILES

Note that the mean δD°/oo values down to a depth of about 103.5 m of ice equivalent are almost identical: -390.8 and -391°/oo. However, an orthogonal correlation carried out on the data adjusted to equivalent sampling conditions gave a correlation coefficient which was not significant. This is in agreement with the previous discussion concerning the variability of the isotopic signal.

A filtering technique was used to reduce the importance of this noise. The technique was developed by Rabiner and Gold (1975), and adapted and improved by Ait Ouatman* in order to solve problems posed by sampling with different step-lengths and end effects. The selection of the width of the filter bands is made after examining the signal spectra so as to cut the filter in zones where the energy is minimal in order to avoid spurious oscillations (side-lobes).

Figure 4 shows the smoothing obtained for the data series corresponding to the two ice cores using filters with cut-off periods of 170 and 512 a, respectively. These smoothed data sets are also shown in Figure 2.

There is no obvious correlation between the oscillations that can be seen for the two cores when the relatively high frequency filter is used, suggesting that the climatic signal is not significant with respect to the noise under these conditions. On the other hand, in spite of certain residual end effects, the smoothed isotopic profiles appear to be in better agreement when the 512 a filter is used,

*Doctorate thesis prepared for the Institut National Polytéchnique de Grenoble, 1981: "Caracterisation des signaux climatiques isotopiques: séries obtenues par carottage en Antarctique".

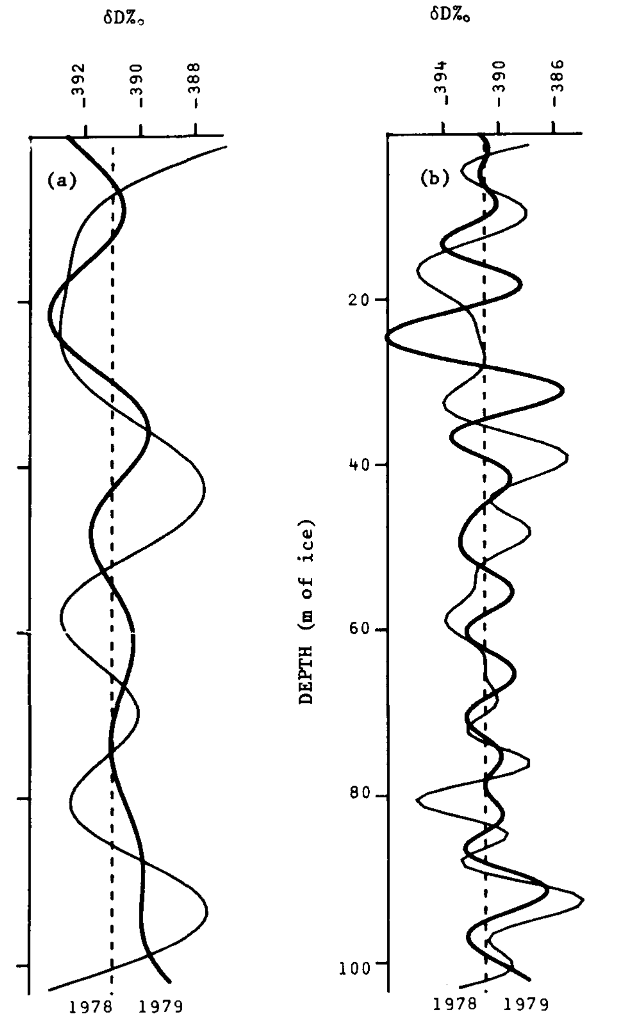

Fig.4. Isotopic profiles from the Dome C ice cores using filter band widths of (a) 512 a and (b) 170 a.

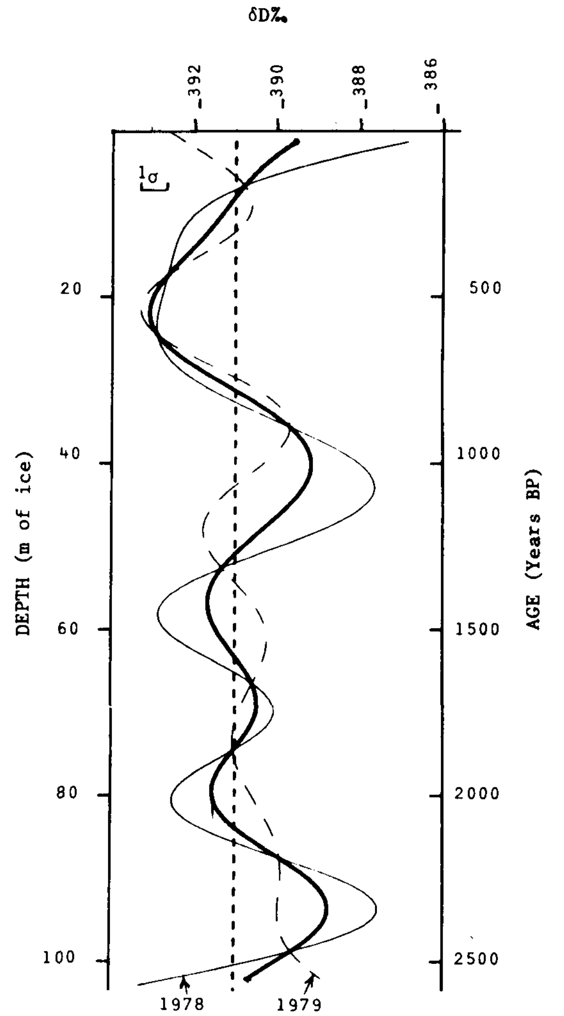

Fig.5. Dome C: averaged isotopic profile for the last 2.5 ka after smoothing with a low pass filter of 512 a.

especially down to a depth of about 30 m with values below the mean for both profiles.

A better description of the climate isotope record can be obtained by combining the two isotopic curves smoothed with the 512 a filter band (Fig.5). The isotopic curve shows intervals where the isotopic signal is successively negative (7 to 31 m ice equivalent depth) and then positive (31 to 51 m depth) with respect to the mean value. The oscillations are then low until a depth of 85 m, after which positive values exist almost down to the bottom of the core. The amplitudes of these oscillations are -2.1, +1.7, and +2.1°/oo, respectively.

With the 512 a filter used, the standard deviation due to the noise is $23/\sqrt{512}.\sqrt{2}$ or 0.7°/oo for the average curve. This suggests that the above oscillations of the climate isotope record are significant.

THE CLIMATIC RECORD OVER THE LAST 2.5 ka FROM THE DOME C ICE CORES

As mentioned in the introduction, the isotopic content of precipitation is mainly governed by condensation temperatures. In Antarctica, the mean temperatures above the inversion layer are similar to the condensation temperatures, while the inversion strength is related linearly to mean surface temperatures (Robin 1977, Lorius and others 1979). As in a previous study (Lorius and others 1979), this allows us to tentatively use the linear relationship between mean δ values and mean surface temperature T obtained by empirical studies (over a wide area which includes the Dome C area) to interpret the mean δ smoothed curve in terms of surface temperature changes.

From the empirical relationship $\delta D°/oo = 6.04(\pm 0.15)T\ (°C) - 51$ (Lorius and Merlivat 1977), a change of 6°/oo/°C is obtained. This value corresponds to a change of 0.7°C for the temperature of condensation and is in very good agreement with the isotopic model of Jouzel and Merlivat (unpublished*).

It must, however, be emphasized that this interpretation is only valid if it is assumed that the average effects of secondary parameters (Robin 1981) have not changed significantly over time. Taking this into account and using a time scale obtained from the mean snow accumulation rate (40 mm of ice equivalent) as discussed above, it is possible to describe the main climatic features over about the last 2.5 ka as depicted by the Dome C δ curve obtained using the 512 a filter (Fig.5).

With respect to the mean conditions, the δ record suggests the existence of a cool period between 1800 and 1200 AD, with an amplitude as high as 0.35°C. This cool period was preceded by a slightly warmer period between 1200 and 700 AD, with an amplitude of

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about 0.3°C. Going further back in time, the temperature seems to have changed little except for a slightly warmer period (amplitude 0.35°C) around 2 300 a BP.

COMPARISON WITH OTHER ANTARCTIC δ TIME SERIES

Unfortunately, no detailed isotope profile covering the last 1 ka is available from other Antarctic sites. However, Budd and Morgan (1977) have suggested, from studies on an ice core drilled in the coastal Law Dome (about 66°S and 113°E), that a generally cooler period began "200 years ago and perhaps even earlier". At the inland Mizuho station (70°42'S, 44°20'E) a discontinuous δ profile shows more negative values for the period 100 to 400 a BP compared to conditions prevailing during this century (Watanabe and others 1978).

Both data sets are in agreement with the Dome C isotope profile, and the slight indication of generally cooler conditions in Antarctica prior to the eighteenth century fits with the recent ice-advance events which occurred about 500 and 265 ^{14}C a BP in the South Shetland Islands (Curl 1980).

COMPARISON WITH SOUTHERN HEMISPHERE CLIMATIC DATA OVER THE LAST 1 ka

Data from the southern hemisphere are very scarce, but temperature results back to 1100 AD were recently obtained in New Zealand (Wilson and others 1979) by measuring the $\delta^{18}O$°/oo concentration of successive layers of a stalagmite. Although there is a rather large scatter in individual values, the 50 a running mean curve indicates warmer conditions between 1100 and 1400 AD, while the climate appears to be cooler during the following centuries. These two periods may well correspond to the main climatic features depicted in the Dome C ice cores, taking into account the dating uncertainties in the New Zealand proxy record.

WORLD-WIDE CLIMATIC TRENDS OVER THE LAST 1 ka

A recent review paper (Wigley 1979) summarizes available information for climatic changes since 1000 AD. The sources come from instrumental and historical data as well as from various proxy data obtained, for instance, from ice cores, tree rings, pollen, glaciers, snow lines, and lake levels. The main feature that emerges for this millenium is the existence of a period cooler than present (approximately 1500 to 1700 AD), which corresponds to the so-called Little Ice Age, characterized in particular by a general advance of glaciers. Records from most northern hemisphere sites show such a feature, although there is a rather complex spatial pattern of relative cooling and warming throughout the period, as pointed out by several investigators (Lamb 1977). There is also evidence that the Little Ice Age affected the southern hemisphere with glacial advances occurring at a number of locations (Denton and Karlen 1973, Burrows 1973 and 1975); however, the peak of this cool period may have been slightly earlier than in the northern hemisphere. This is also suggested by data from Patagonia (Mercer 1970), indicating ice re-advance as early as 1300 AD, and by the Dome C δ record.

Prior to this cool period, many records from the northern hemisphere indicate a period as warm or warmer than today, i.e. the medieval warm phase between 800 to 1000 and 1200 AD. However, this period appears much more complicated in terms of temporal and spatial changes. Except for the stalagmite climatic record already cited, which also indicates a warm period from 1100 to 1200, there are apparently no other southern hemisphere data available.

CONCLUSION

Significant noise in the isotope record obtained at Dome C appears to be mainly related to irregularities in the snow accumulation. A high level of smoothing was required in order to reduce this noise in the data.

However, in spite of the many limitations in the interpretation of our Dome C ice-core results, the smoothed isotopic record suggests that the world-wide climatic events over the last 1 ka (the Little Ice Age and the somewhat less-defined warm medieval period) may have also affected the interior of East Antarctica. Many other sites need to be investigated to verify this tentative interpretation of our data, especially in zones of greater and more regular snow accumulation, such as the South Pole, as suggested by a study concerning the last 100 a using samples from this site (Jouzel and others unpublished*).

ACKNOWLEDGEMENTS

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