Annals of Glaciology 5 1984

LATE-GLACIAL MAXIMUM-HOLOCENE ATMOSPHERIC AND ICE-THICKNESS CHANGES FROM ANTARCTIC ICE-CORE STUDIES

by

C. Lorius, D. Raynaud and J.-R. Petit,

(Laboratoire de Glaciologie et Géophysique de l'Environnement, 2 rue Très-Cloîtres, 38031 Grenoble Cedex, France)

J. Jouzel and L. Merlivat

(Laboratoire de Géochimie Isotopique, Département de Physico-Chimie, Centre d'Études Nucléaires de Saclay, Boîte Postale 2, 91190 Gif sur Yvette Cedex, France)

ABSTRACT

A review of Byrd, Vostok and Dome C Antarctic ice-core records indicates significant changes in atmospheric characteristics between the late glacial maximum (LGM) and the Holocene. This data is relevant to general circulation model (GCM) boundary conditions and validation of output results. Reciprocally, GCM data could help to interpret ice-core results and to extend observed high-latitude changes to a larger scale.

During the LGM, low troposphere temperatures were colder by about 5 to 7°C and surface temperatures by 8 to 10°C over the Antarctic ice sheet. There are indications that snow accumulation was slightly lower and isotopic data suggests higher relative humidity over the ocean. A large increase in continental dust (up to a factor of 20) and marine aerosols (up to a factor of 5) is observed on the high Antarctic plateau, both explained by the increased (possibly up to 1.4 to 2 times) intensity of the large-scale atmospheric circulation modulated by desert and sea-ice area extension. Ice-core results show large changes in atmospheric CO_2 concentrations with LGM values around 200 ppmv and "pre-industrial" values of about 260 ppmv. Finally, determinations of total gas content suggest that central West and East Antarctica were not thicker during the LGM, in contrast with higher surface elevations inferred from coastal-ice studies.

INTRODUCTION

An increasing number of parameters of climatic significance are being determined in ice cores, providing a record of past conditions. The obtained data are relevant to boundary conditions prescribed by an atmospheric global circulation model (GCM) and for the validation of output results. Reciprocally, GCM calculations could help to assess the validity of some of the interpretations of the ice-core records which are not straightforward, and to connect and extend high-latitude changes to a much larger scale. The late-glacial maximum (LGM) is of particular interest for palaeoclimatic GCM reconstructions.

In central areas of the ice sheet, one ice record from West Antarctica (Byrd) and two from East Antarctica (Vostok, Dome C) extend back to the LGM. Such a period is also covered by a few drillings in the coastal area of East Antarctica (Law Dome, Terre Adélie) but in such sites the climatic records are highly disturbed by ice-flow effects. In this paper we review climatic LGM-Holocene changes inferred from inland ice records in Antarctica; information about ice-thickness changes will also be discussed for coastal drillings.

Due to the present lack of adequate absolute-dating techniques, the time scale of the ice records has been obtained by ice-flow model calculations. Although it is not possible to determine very accurate ages in this way, the chronologies proposed for the central Antarctic ice cores are in sufficient agreement to characterize the LGM and Holocene stages and to compare the obtained climatic records.

ATMOSPHERIC DATA

Temperature from isotope climatic records

The $\delta^{18}O$ isotope shifts associated with the LGM-Holocene transition (Figs.1, 2 and 3) are about 7‰ for Byrd (Johnsen and others 1972), 5‰ for Vostok (Barkov and others 1977) and 5.4‰ for Dome C (Lorius and others 1979). An interpretation in terms of temperature changes is complicated because the isotopic composition of the precipitation is governed not only by its temperature of formation T_F but also depends on the origin and history of the air masses, on the condensation processes involved, and on its altitude of formation. The mean $\delta^{18}O$ content of modern precipitation decreases with mean surface temperature T_S, and a very well-fitted linear relationship ($r = 0.989$) is observed from -22 to -55°C over East Antarctica with a gradient of 0.75‰ $°C^{-1}$ (Lorius and Merlivat 1977). This and other facts (Robin 1977) suggest the possibility of reconstructing past temperatures from isotopic data. A simple isotopic model recently developed (Jouzel and Merlivat to be

https://doi.org/10.3189/1984AoG5-1-88-94 Published online by Cambridge University Press

published*) suggests that the influence of the altitude of formation of the precipitation is negligible and that the effect of the sea-water temperature in the vapour source area may be small at least for inland stations. Due to supersaturation over ice, snow is formed out of isotopic equilibrium and the calculated $\delta^{18}O/T_F$ gradient shows a rather constant value of about 1.2^o/oo °C^{-1}. As suggested by Robin (1977), T_F is rather close to the temperature T_I prevailing above the thin inversion layer, while the inversion strength is linearly related to T_S, with $dT_I/dT_S = 0.67$ (Lorius and others 1979). A theoretical value of 0.8^o/oo °C^{-1} is thus inferred for $d\delta^{18}O/dT_S$, a figure very close to the experimental gradient (0.75^o/oo) observed over East Antarctica. This good agreement leads us to use this theoretical value for a tentative estimation of past temperature changes although there are obvious insufficiencies in this approach (i.e. the model is based on ideal isolated air masses and there is no available experimental gradient over West Antarctica); further improvements may be expected from the simulation of isotopic cycles with GCMs (Joussaume and others 1984[b], in which changes in the source area and in the dynamic history of the air masses can be taken into account, and from further data obtained concerning the present δ distribution, in particular in West Antarctica.

The observed LGM-Holocene isotopic shifts must first be corrected for the increase (1.6^o/oo) in the mean $\delta^{18}O$ content of oceanic waters during the LGM (Duplessy 1978). The corrected isotopic changes are then 8.6^o/oo for Byrd, 6.6^o/oo for Vostok and 7^o/oo for Dome C, leading to respective T_F changes of about 7, 5.5 and 6°C. These values refer to low troposphere conditions, above the inversion layer, while the derived surface temperature T_S changes are about 10 and 8 to 9°C.

These tentative estimated temperature values may include effects linked with changes in the ice-formation site and in ice-sheet surface topography. As discussed in another section, very low velocity and ice-thickness changes suggest that these effects may be very small for central East Antarctica sites although for West Antarctica (Byrd), LGM ice may originate from a distance of about 100 km. The Antarctic isotopic records from central areas therefore seem mainly to reflect atmospheric temperature changes; this is further supported by the comparison of the δ profiles which show not only the same trends and comparable amplitude for the LGM-Holocene transition, but have also recorded the same significant shorter-term events, which are more likely climatic features than ice-sheet dynamic effects. As also previously pointed out (Lorius and others 1979), the climatic history of the last 30 ka thus inferred from ice cores is in fact in very good agreement with available southern hemisphere proxy data. Further support of our estimated temperature changes comes from ice crystal-size changes (Duval and Lorius 1980) with depth. The decrease observed during the LGM-Holocene transition can in fact be interpreted by surface temperature changes which affected the crystal growth; the estimated temperature variation for Dome C is in very good agreement with the one inferred from the δ record (Petit and others to be published**).

Relative humidity over the ocean from isotope records

It was recently suggested (Merlivat and Jouzel 1979) that, when considering two different periods, the variation of the deuterium excess in precipitation ($d = \delta D - 8\ \delta^{18}O$) can be used to estimate the variation of the relative humidity h over the source region of the precipitating air mass. A theoretical approach can be used to discuss the possible influence of various factors and indicates that d is linearly dependent on h (Jouzel and others 1982); with d = 10 (the mean value of modern precipitation), an h value of 81% is inferred which is very close to the value that actually prevails over the ocean surface. The main feature of the d profile obtained from the Dome C ice core (Fig.1) is the gradual change of 4.5^o/oo between the LGM and 7.5 ka BP. This shift has been interpreted (Jouzel and others 1982) as reflecting a higher value of h over ocean areas providing moisture for Antarctica (south of 40°S), estimated around 90% for LGM conditions through $\Delta d = -45\ \Delta h$. We keep in mind that there are many assumptions in the derivation of this relationship; nevertheless similar changes may have also affected the tropical and equatorial regions (Merlivat and Jouzel 1979, Flohn 1981). Its possible hemispheric and even global significance must still be confirmed, both by further experimental data and by GCM simulation of LGM climate.

Marine aerosol concentration changes have been connected with wind intensity U over oceanic source areas (Petit and others 1981). The correlation observed between d and Na concentration (Fig.1) thus suggests a link between h and U. It has been proposed (Jouzel and others 1982) that this link results from the constant value of U(1-h) for LGM and Holocene conditions, inferred from evaporation flux and energy-balance considerations. An increase of 10% for h then also suggests an increase in the wind speed over the oceanic source area by a factor of about 2 during the LGM, in agreement with the figure obtained from marine aerosols.

Snow accumulation

Due to the present lack of adequate absolute dating techniques and of convincing results on seasonal changes of geochemical parameters for deep ice, there is no direct evidence of changes in snow accumulation A. At Dome C, favourable glaciological conditions suggest that the time scale is linearly related to 1/A. Direct determination of A in the surface layers and the comparison of the ice isotopic record with a suitable ^{14}C-dated (Duplessy and others 1980) marine isotopic profile from the Indian Ocean was used to estimate that A remained rather constant over the Holocene but decreased with a colder climate, the accumulation 14 ka BP being about 75% of the present value (Lorius and others 1979). Since then the validity of this assumption has been confirmed, with a further check on the obtained chronology, by the existence of continental dust indexes about 26 and 13 ka BP (Fig.1) attributed to the beginning and end of an aridity period (^{14}C dated) over southern hemisphere continents (Bowler 1976). As suggested by Robin (1977), the accumulation appears to be primarily governed by the amount of water vapour that can be carried in the air mass above the inversion. The temperature changes deduced above would imply a decrease of about 40% for Dome C and Vostok, and of about 60% for Byrd. However this reduction may be partially compensated by the increase in air fluxes over Antarctica during the LGM as discussed in this paper. GCM simulations would help to clarify the scarce evidence of climate related accumulation changes over Antarctica.

Aerosols

From theoretical considerations (Junge 1979) and experimental determinations (Pourchet and others 1983) it is generally assumed that the concentration of impurities in the precipitation is directly related to the concentration in the atmosphere. This assumption, which should be further investigated, is the basis for reconstructing past aerosol data from ice-core records. The three Antarctic ice cores show

*To be published:
Jouzel J, Merlivat L Deuterium and oxygen 18 in precipitation. Modelling of the isotopic effect at snow formation.

**To be published:
Petit J-R *and others* Ice crystal growth rate in East Antarctica core samples: a new palaeoclimatic tool.

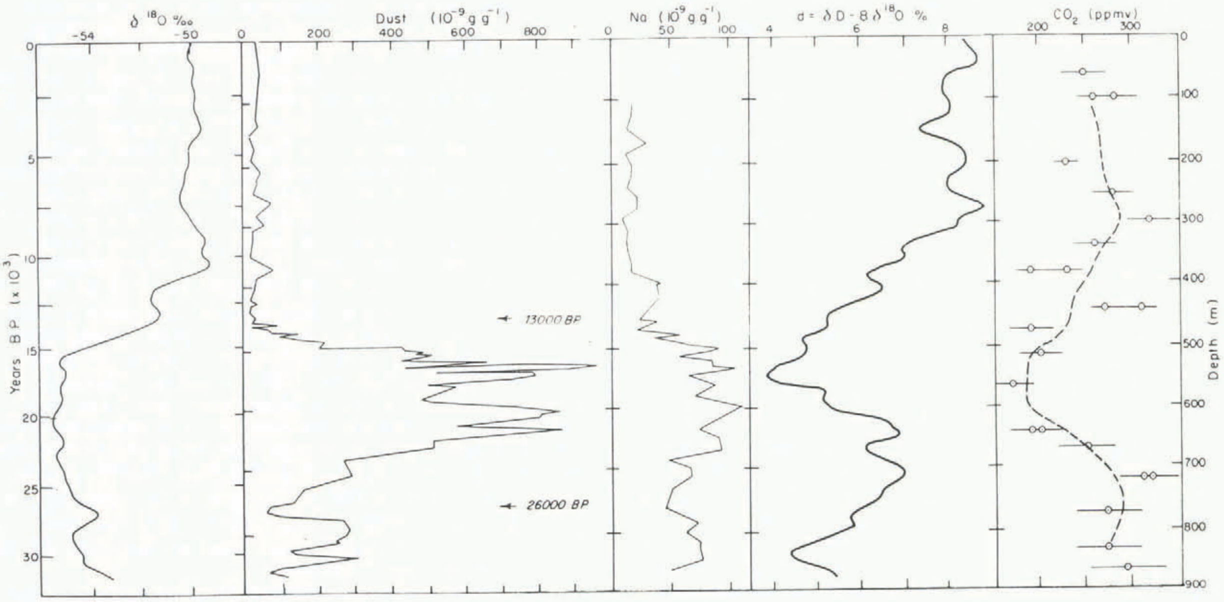

Fig.1. The Dome C record. Smoothed $\delta^{18}O$ (‰) (from Lorius and others 1979), dust and marine Na concentrations (from De Angelis and others in press, Royer and others in press), deuterium excess d (from Jouzel and others 1982), and CO_2 concentrations (individual measurements and running means, adapted from Delmas and others (1980)) plotted versus age and depth (m of ice).

very large changes over the last 30 ka (Cragin and others 1977, Petit and others 1981, Thompson and Mosley-Thompson 1981, De Angelis and others in press) with very large values around the LGM which cannot be explained by possible accumulation changes.

Elemental determinations (Si, Al) and scanning electron microscope observation and analysis indicate an influx of dust at this time which is mainly of continental origin (Cragin and others 1977, Petit and others 1981, Briat and others 1982) even if the Byrd core shows many ash layers which may have a local volcanic origin. The LGM/Holocene ratio is 4 for Byrd, 24 for Vostok and 17 for Dome C. The high LGM dust value has been interpreted as reflecting both the extension (x 5) of arid continental sources in the southern hemisphere (Sarnthein 1978) due to a dry environment (CLIMAP Project Members 1981) and stronger winds. Antarctic ice cores, therefore, probably record record large-scale environmental changes; the high elevations of Dome C (3 240 m) and Vostok (3 420 m) suggest that they are more representative than Byrd (1 500m) of the background atmospheric dust which travels at elevations higher than 3 000 m in the troposphere (Delany and others 1973), although the dust repartition may not be homogeneous over all Antarctica. Assuming a constant snow accumulation and a dust flux over the high East Antarctic plateau proportional to the flux over the sources, an increase in wind velocity by a factor of about 1.4 has been calculated for the source areas (Petit and others 1981). This is a maximum value since the transport efficiency which is linked to turbulence has also played a role as demonstrated by the presence of microparticles as large as 10 μm in LGM ice samples (Petit and others 1981). Such a wind velocity increase is probably connected with an increase in the temperature gradient with latitude during the LGM (CLIMAP Project Members 1981) over the southern hemisphere.

Marine aerosol concentrations are also higher during the LGM (see Na in Fig.1) with LGM/Holocene ratios of about 2 to 3 for Byrd (Cragin and others 1977), 4 to 5 for Vostok (De Angelis and others in press) and 5 for Dome C (Petit and others 1981). These higher values may also be explained by an increase in the wind over the Southern Ocean (40 to 50°S wind belt), with the effect of the sea-ice extension during the LGM (CLIMAP Project Members 1981) compensated by a higher transport efficiency. The comparison of Na and $\delta^{18}O$ profiles (Fig.1) shows that marine aerosol concentrations increase as climate gets colder; they both probably reflect Antarctic and sub-Antarctic changes. Differences between sites for the LGM/Holocene ratios may tentatively be explained by deeper penetration of cyclonic disturbances associated with a higher meridional temperature gradient during the LGM (De Angelis and others in press).

The main ionic constituents such as sulphate and nitrate also show higher concentrations during the LGM. The increase for SO_4^{2-}, about x 1.5 at Byrd (Cragin and others 1977) and about 2 to 3 for East Antarctic sites (M Legrand in preparation), is likely to be associated with an increase in the marine contribution. Legrand also found a threefold increase for nitrates in LGM Dome C ice samples. Assuming that the concentrations measured in the ice reflect atmospheric changes, LGM aerosol concentrations were then higher by about x 5 to 6 (Royer and others in press).

The high aerosol loading of the LGM atmosphere has probably affected the radiation balance. A tentative estimate (Royer and others in press) suggests a warming effect over Antarctica smaller than 2°C and a relative heating rate significantly higher over the dust sources, e.g. tropical desert areas. This suggests a possible significant change in one of the boundary conditions, i.e. the atmospheric composition, prescribed in atmospheric GCM palaeoclimatic simulations.

Antarctic ice cores have recorded significant changes of aerosol concentrations in the regional low troposphere. A three-dimensional picture over Antarctica and reconstitution up to the source areas may not be achieved without the help of atmospheric circulation models (Joussaume and others 1984[a]); the ice-core data may potentially be used as a check on such simulations. A significant increase (by a factor of 2.5) in concentration of the cosmogenic ^{10}Be has also been observed in the LGM Dome C samples with respect to rather constant Holocene values (Raisbeck and others 1981). The climatic implications are not clear at present as such a change may be related to various parameters, i.e. snow accumulation, atmospheric exchanges, primary cosmic-ray and geomagnetic field intensity, and solar activity.

Carbon dioxide (CO_2)

When firn turns into ice, atmospheric air is entrapped as bubbles. Using appropriate gas-extraction procedures (Raynaud and others 1982) it is possible to obtain, from cold ice cores, a record reflecting the past evolution of the atmospheric CO_2 content. Although different processes may complicate the interpretation of the CO_2 measurements in air bubbles in ice (Lorius and Raynaud 1983), this method provides the most direct evidence for such an atmospheric record.

For the record extending back to the LGM, the most relevant Antarctic data was obtained from the Dome C and Byrd cores (Delmas and others 1980, Neftel and others 1982). Although there is significant scatter in the data which could reflect both experimental problems and natural fluctuations, the following features are clearly apparent: CO_2 values for the LGM are of the order of 200 ppmv; for the Holocene period the records indicate a mean figure of about 270 ppmv (Figs.1 and 2). These values are consistent with the results obtained from other ice cores (Delmas and others 1980, Neftel and others 1982). More recent measurements performed on both cores indicate that between about 800 and 2 500 a BP, which is before the significant anthropogenic perturbation of the atmospheric CO_2, the CO_2 concentration was of the order of 260 ppmv (Barnola and others 1983). This figure should be compared with the CO_2 concentration measured in the atmosphere since 1958, which is today around 340 ppmv. A new study of the D57 core (East Antarctica suggests a value of about 260 ppmv around 1850 AD and the existence of slight natural variations before this time (Raynaud and Barnola 1984).

Thus, according to ice-core data, important changes have occurred in the CO_2 atmospheric reservoir since the LGM; the same relative increase is observed with very different climatic changes: the first increase (from 200 to 270 ppmv) is linked with the drastic LGM-Holocene climatic change and the second (from 260 to 340 ppmv) corresponds to a period with relatively stable temperature conditions.

If the CO_2 change measured in the atmosphere between 1958 and today is mainly attributed to the effect of the fossil fuel consumption, causes for earlier variations are more difficult to assess. Part of the change that has occurred since the 260 ppmv level, which could be representative of the pre-1850 AD atmosphere, may be due to a biospheric CO_2 source induced by mankind before the use of fossil fuel (Lorius and Raynaud 1983, Raynaud and Barnola 1984). On the other hand the increase in the CO_2 concentration, which occurred between the LGM and the Holocene period, was forced by natural mechanisms. Recent explanations involve changes in the marine biological productivity (Broecker 1982, McElroy 1983) or in the reef-building activity (Berger 1982) linked with the sea-level rise following the melting of the ice sheets; possible modification in the oceanic circulation may also play a primordial role (Broecker and Takahashi 1984, Stauffer and others 1984). A precise study of the comparative timing between the CO_2 and climate changes inferred from ice-core records may provide important information in this respect. New results obtained from the Dome C core suggest that the interpretation of this comparative timing near the end of the LGM could be complex because of the "stepped" shape of the CO_2 variation (Raynaud and Barnola 1984).

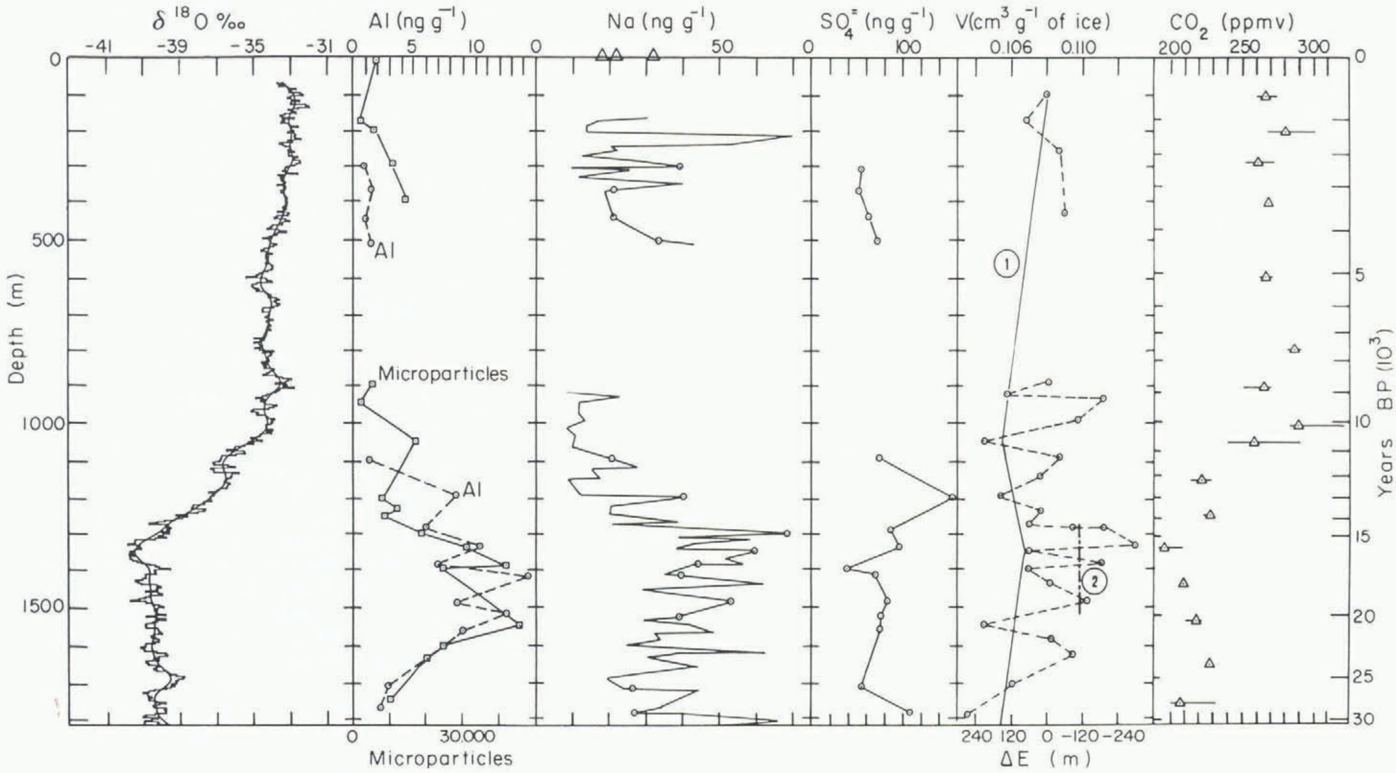

Fig.2. The Byrd record. $\delta^{18}O$ ($^{o}/oo$), aluminium and microparticle content, total Na and SO_4^{2-} concentrations, total gas V, and CO_2 content versus age and depth. $\delta^{18}O$ ($^{o}/oo$) and the chronology are from Johnsen and others (1972); the δ values versus depth provided by W Dansgaard have been smoothed using a spline function. Microparticle (greater than 0.62 μm per 500 μl sample) content is from Thompson (1977). Al, Na and SO_4^{2-} values: circles are from Cragin and others (1977), points are from Ragone and Finelli (1972), Δ are surface-compiled values from Briat (1974). V results are from Raynaud and Whillans (1982); the difference between lines (1) and (2) for the LGM ice indicates that the Byrd area was lower than at present by about 175 to 205 m (from the ΔE scale given in the figure). CO_2 concentrations are from Neftel and others (1982) and Oeschger and others (1982).

ICE-THICKNESS DATA

The total gas content V in ice depends theoretically on the atmospheric pressure P and temperature T, and on the ice-pore volume V_c when the firn turns into ice (Raynaud 1977). Raynaud and Lebel (1979) found an experimental relationship between V and the elevation E of the ice-formation site under present conditions:

$$V[\mathrm{cm}^3\ \mathrm{g}^{-1}\ \text{of ice}] = -1.66 \times 10^{-5}\ \mathrm{Em} + 0.138$$

This equation implies that V_c decreases linearly with temperature and we can assume that the variations of V with E are only due to the changes of P and T according to:

$$V[\mathrm{cm}^3\ \mathrm{g}^{-1}\ \text{of ice}] = \left(2.0 \times 10^{-4} - \frac{0.015}{T\ (K)}\right) P[\mathrm{mbar}]$$

(Raynaud and Lebel 1979). At constant pressure, V would then decrease as the temperature decreases at a rate of about 2×10^{-4} $\mathrm{cm}^3\ \mathrm{g}^{-1}$ of ice per °C. Although the physical mechanisms causing the V_c-T_c dependence are not clearly understood, application of the above empirical figures is the most direct way to obtain information about past ice-surface elevation.

The application to LGM conditions first requires a correction for changes in T which can be obtained, as previously discussed, from isotopic shifts. An uncertainty remains with regard to possible changes of the atmospheric pressure field which could, in particular, be connected with different circulation patterns. Due to the lack of information, which could probably be obtained from atmospheric palaeo-simulations, we will assume in our interpretations that the elevation-pressure pattern did not change with time.

When the elevation of the ice-formation site is thus obtained, we have to assess ice-flow conditions so that the past surface elevation may be reconstructed, which will, in turn, reflect the past ice thickness. For the Byrd ice core, Raynaud and Whillans (1982) calculated the expected V profile from steady-state conditions, i.e. assuming a surface elevation

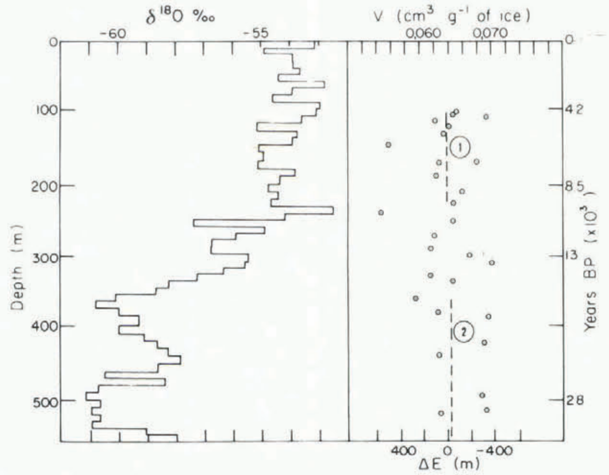

Fig.3. The Vostok record. $\delta^{18}O$ (°/oo) from Kotlyakov and Gordiyenko (1982) and total gas content V versus depth and age from Korotkevich and others (to be published*). For the V record a scale in terms of elevation change is also given; the difference between dashed lines 1 and 2 ($\Delta E \simeq -30$ m) indicates that the LGM ice was formed at an elevation close to the current Vostok altitude.

profile constant with time, upstream from Byrd station. Note that the "steady-state" line (1) in Figure 2 is slightly different from the one given by Raynaud and Whillans because a surface temperature change of 10°C (as discussed previously) linked to the termination of the LGM has been used instead of a value of 7°C. Figure 2 indicates a significant deviation between the "steady-state" curve and the V experimental results in the depth interval corresponding to the LGM. This deviation suggests that the surface elevation at the ice formation site, estimated to be at about 100 km upstream from the drilling site (Whillans 1979), was lower than present by about 175 to 205 m. Keeping in mind the limitations of this method, the gas information strongly suggests that the ice thickness around Byrd did not change dramatically at the same time that the last ice age ended. The gas evidence is consistent with another study based on the interpretation of internal radio echo layers (Whillans 1976). The behaviour of the Byrd area between the LGM and present conditions may be typical of the central area of West Antarctica.

For the central part of East Antarctica the only available data including the LGM comes from the Vostok core (Korotkevich and others to be published*). Although the experimental procedure used lacks accuracy, the results suggest that the LGM ice was formed at an elevation close to the current Vostok altitude. From ice velocities at the order of a few metres per year (Young 1979) and the present day surface elevation contours, we can estimate that the LGM ice was formed a few tens of kilometres from the present drilling site at an elevation which was about 100 m lower than the current one. The Vostok gas results are consistent with the interpretation of the temperature profile measured in the Dome C bore hole (Ritz and others 1982). They both suggest a slight thickening of this central part of East Antarctic since the end of LGM but, in any case, no dramatic change.

The interpretation of the combined V-δ obtained from ice cores drilled in some East Antarctica coastal sites is less straightforward, due to the significant ice-flow effects. Nevertheless, results from the D-10 (66°40'S 140°01'E) core in Terre Adélie suggest that the surface elevation about 250 km from the present coast was of the order of 400 m higher during the LGM than now (Raynaud and others 1979, Young and others 1984). Other V results from the Cape Folger F core suggest that the ice-thickness change for the area of the Law Dome near Casey (66°17'S 110°32'E) was even larger (Budd and Morgan 1977, Lebel 1979).

In conclusion, the interpretation of the limited available V data indicates a possible slight thickening of the central parts of the ice sheet and a more significant thinning of some coastal areas in East Antarctica since the LGM. This picture differs from the one given by some reconstructions (e.g. Hughes and others 1981), based on ice-sheet modelling, which conclude a much thicker West Antarctica during the LGM. A slight thickening of central West Antarctica between the LGM and the Holocene could have been induced by an increase in the rate of snow accumulation (Raynaud and Whillans 1982), an explanation which could also hold for central East Antarctica. On the other hand, coastal areas could have thinned between the LGM and the present under the influence of the sea-level rise and the temperature increase.

However much more experimental data and ice-sheet modelling efforts are required to sort out a realistic picture of Antarctic ice surface elevation changes since the last ice age.

* To be published:
Korotkevich Ye S, Petrov V N, Barkov N I, Lipenkov V Ya Vertical structure of the Antarctic ice sheet and palaeogeographic interpretation of the data obtained.

CONCLUSION

The review of available Antarctic ice-core data from inland sites and covering both Holocene and LGM suggests very drastic modifications of the atmospheric environment. Some have a regional significance; the proposed temperature and suggested accumulation changes could provide useful comparisons with GCM results. Others may have impact on a hemispheric scale (aerosol concentrations, relative humidity over the ocean); the inferred changes for the wind velocity and relative humidity could again be checked with atmospheric model outputs. Aerosols may have changed the radiation balance and when feasible should be included as prescribed boundary conditions in model simulation. This also applies to carbon dioxide, as the large changes recorded in Antarctic ice are of a global significance and may have played, through strong interactions between continents, atmosphere and oceans, a major role in the LGM-Holocene climatic change. In contrast with the drastic modifications of the atmospheric environment, ice-core data suggest only slight changes in central Antarctic ice thicknesses since the LEM, but more pronounced changes in the coastal areas; central and marginal areas of the ice sheet could have reacted differently to the climatic change.

REFERENCES

Barkov N I, Korotkevich E S, Gordienko F G, Kotlyakov V M 1977 The isotope analysis of ice cores from Vostok station (Antarctica), to the depth of 950 m. *International Association of Hydrological Sciences Publication* 118 *(General Assembly of Grenoble 1975 - Isotopes and Impurities in Snow and Ice)*: 382-387

Barnola J M, Raynaud D, Neftel A, Oeschger H 1983 Comparison of CO_2 measurements by two laboratories on air from bubbles in polar ice. *Nature* 303 (5916): 410-413

Berger W H 1982 Increase of carbon dioxide in the atmosphere during deglaciation: the coral reef hypothesis. *Naturwissenschaften* 69: 87-88

Bowler J M 1976 Aridity in Australia: age, origins and expression in aeolian landforms and sediments. *Earth Science Reviews* 12: 279-310

Briat M 1974 Dosage du chlore, du sodium et du manganèse par activation neutronique dans le névé antarctique: origine et retombée de ces éléments. *Laboratoire de Glaciologie du Centre National de la Recherche Scientifique. Publication* 166

Briat M, Royer A, Petit J-R, Lorius C 1982 Late glacial input of eolian continental dust in the Dome C ice core: additional evidence from individual microparticle analysis. *Annals of Glaciology* 3: 27-31

Broecker W S 1982 Ocean chemistry during glacial time. *Geochimica et Cosmochimica Acta* 46(10): 1689-1705

Broecker W S, Takahashi T 1984 Is there a tie between atmospheric CO_2 content and ocean circulation? (Abstract) *Annals of Glaciology* 5: 201

Budd W F, Morgan V I 1977 Isotopes, climate and ice sheet dynamics from core studies on Law Dome, Antarctica. *International Association of Hydrological Sciences Publication* 118 *(General Assembly of Grenoble 1975 - Isotopes and Impurities in Snow and Ice)*: 312-321

CLIMAP Project Members 1981 Seasonal reconstructions of the Earth's surface at the last glacial maximum. *Geological Society of America Map and Chart Series* MC-36

Cragin J H, Herron M M, Langway C C Jr, Klouda G 1977 Interhemispheric comparison of changes in the composition of atmospheric precipitation during the late Cenozoic era. *In* Dunbar Maxwell J (*ed*) *Polar Oceans. Proceedings of the polar oceans conference...Montreal...1974.* Calgary, Arctic Institute of North America: 617-631

De Angelis M, Jouzel J, Lorius C, Merlivat L, Petit J-R, Raynaud D In press Ice age data for climate modelling from an Antarctic (Dome C) ice core. *In* Berger A (*ed*) *Proceedings of the Symposium on new perspectives in climate modelling: 9th General Assembly of the European Geophysical Society, Leeds, 1982.* Amsterdam, Elsevier Scientific Publishing Company

Delany A C, Pollock W H, Shedlovsky J P 1973 Tropospheric aerosol: the relative contribution of marine and continental components. *Journal of Geophysical Research* 78(27): 6249-6265

Delmas R J, Ascencio J-M, Legrand M 1980 Polar ice evidence that atmospheric CO_2 20,000 yr BP was 50% of present. *Nature* 284(5752): 155-157

Duplessy J-C 1978 Isotope studies. *In* Gribbin J (*ed*) *Climatic change.* Cambridge etc, Cambridge University Press: 46-67

Duplessy J-C, Moyes J, Pujol C 1980 Deep water formation in the North Atlantic Ocean during the last ice age. *Nature* 286(5722): 479-482

Duval P, Lorius C 1980 Crystal size and climatic record down to the last ice age from Antarctic ice. *Earth and Planetary Science Letters* 48(1): 59-64

Flohn H 1981 Tropical climate variations during late Pleistocene and early Holocene. *In* Berger A (*ed*) Climatic variations and variability: facts and theories. *In NATO Advanced Study Institute, first course of the International School of Climatology, Ettore Majorana Center for Scientific Culture, Erice, Italy, March 9-21, 1980.* Dordrecht, Reidel Publishing Co.: 233-242 (NATO Advanced Study Institute Series C 72)

Hughes T J, Denton G H, Andersen B G, Schilling D H, Fastook J L, Lingle C S 1981 The last great ice sheets: a global view. *In* Denton G H, Hughes T J (*eds*) *The last great ice sheets.* New York etc, John Wiley and Sons: 263-317

Johnsen S J, Dansgaard W, Clausen H B, Langway C C Jr 1972 Oxygen isotope profiles through the Antarctic and Greenland ice sheets. *Nature* 235(5339): 429-434

Joussaume S, Rasool I, Sadourny R, Petit J-R 1984[a] Simulation of desert dust cycles in an atmospheric general circulation model (Abstract). *Annals of Glaciology* 5: 204-207

Joussaume S, Sadourny R, Jouzel J 1984[b] Simulation of the HDO and $H_2{}^{18}O$ cycles in an atmospheric general circulation model (Abstract). *Annals of Glaciology* 5: 208-210

Jouzel J, Merlivat L, Lorius C 1982 Deuterium excess in an East Antarctic ice core suggests higher relative humidity at the oceanic surface during the last glacial maximum. *Nature* 299(5885): 688-691

Junge C E 1979 The importance of mineral dust as an atmospheric constituent. *In* Morales C (*ed*) *Saharan dust; mobilization, transport, deposition. SCOPE 14.* Chichester etc, John Wiley and Sons: 49-60

Kotlyakov V M, Gordiyenko F G 1982 *Izotopnaya i geokhimicheskaya glyatsiologiya* [*Isotope and geochemical glaciology*]. Leningrad, Gidrometeoizdat

Lebel B 1979 Porosité et teneur en gaz de la glace polaire récente; applications à l'étude des carottes prélevées en profondeur. *Laboratoire de Glaciologie du Centre National de la Recherche Scientifique. Publication* 255

Lorius C, Merlivat L 1977 Distribution of mean surface stable isotope values in East Antarctica: observed changes with depth in the coastal area. *International Association of Hydrological Sciences Publication* 118 *(General Assembly of Grenoble 1975 - Isotopes and Impurities in Snow and Ice)*: 127-137

Lorius C, Raynaud D 1983 Record of past atmospheric CO_2 from tree-ring and ice core studies. *In* Bach W, Crane A, Berger A, Longhetto A (*eds*) *Carbon dioxide; a text on current views and developments in energy/climate research.* Dordrecht, Reidel Publishing Co.: 145-176

Lorius C, Merlivat L, Jouzel J, Pourchet M 1979 A 30,000-yr isotope climatic record from Antarctic ice. *Nature* 280(5724): 644-648

McElroy M B 1983 Marine biological controls on atmospheric CO_2 and climate. *Nature* 302(5906): 328-329
Merlivat L, Jouzel J 1979 Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation. *Journal of Geophysical Research* 84 (C8): 5029-5033
Neftel A, Oeschger H, Schwander J, Stauffer B, Zumbrunn R 1982 Ice core sample measurements give atmospheric CO_2 content during the past 40,000 yr. *Nature* 295(5846): 220-223
Oeschger H, Stauffer B, Neftel A, Schwander J, Zumbrunn R 1982 Atmospheric CO_2 content in the past deduced from ice-core analyses. *Annals of Glaciology* 3: 227-232
Petit J-R, Briat M, Royer A 1981 Ice age aerosol content from East Antarctic ice core samples and past wind strength. *Nature* 293(5831): 391-394
Pourchet M, Pinglot F, Lorius C 1983 Some meteorological applications of radioactive fallout measurements in Antarctic snow. *Journal of Geophysical Research* 88(C10): 6013-6020
Ragone S E, Finelli R V 1972 Cationic analysis of the Byrd station, Antarctica, ice core. *CRREL Special Report* 180
Raisbeck G M *and 6 others* 1981 Cosmogenic ^{10}Be concentrations in Antarctic ice during the past 30,000 years. *Nature* 292(5826): 825-826
Raynaud D 1977 Les inclusions gazeuses dans la glace de glacier; leur utilisation comme indicateur du site de formation de la glace polaire; applications climatiques et rhéologiques. *Laboratoire de Glaciologie du Centre National de la Recherche Scientifique. Publication* 214
Raynaud D, Barnola J M 1984 The CO_2 record in ice cores: a reconstruction of the atmospheric evolution between 18 ka BP and 1850 AD (Abstract). *Annals of Glaciology* 5: 224
Raynaud D, Lebel B 1979 Total gas content and surface elevation of polar ice sheets. *Nature* 281(5729): 289-291
Raynaud D, Whillans I M 1982 Air content of the Byrd core and past changes in the West Antarctic ice sheet. *Annals of Glaciology* 3: 269-273
Raynaud D, Lorius C, Budd W F, Young N W 1979 Ice flow along an I.A.G.P. flow line and interpretation of data from an ice core in Terre Adélie, Antarctica. *Journal of Glaciology* 24(90): 103-115
Raynaud D, Delmas R, Ascencio J-M, Legrand M 1982 Gas extraction from polar ice cores: a critical issue for studying the evolution of atmospheric CO_2 and ice-sheet surface elevation. *Annals of Glaciology* 3: 265-268
Ritz C, Lliboutry L, Rado C 1982 Analysis of a 870 m deep temperature profile at Dome C. *Annals of Glaciology* 3: 284-289
Robin G de Q 1977 Ice cores and climatic change. *Philosophical Transactions of the Royal Society of London* Ser B 280(972): 143-168
Royer A, De Angelis M, Petit J-R In press A 30,000 yr record of physical and optical properties of microparticles from an East Antarctic ice core and implications for paleoclimate reconstruction models. *Climatic Change*
Sarnthein M 1978 Sand deserts during glacial maximum and climatic optimum. *Nature* 272(5648): 43-46
Stauffer B, Hofer H, Oeschger H, Schwander J, Siegenthaler U 1984 Atmospheric CO_2 concentration during the last glaciation. *Annals of Glaciology* 5: 160-164
Thompson L G 1977 Microparticles, ice sheets and climate. *Ohio State University. Institute of Polar Studies. Report* 64
Thompson L G, Mosley-Thompson E 1981 Microparticle concentration variations linked with climatic change: evidence from polar ice cores. *Science* 212(4496): 812-815
Whillans I M 1976 Radio-echo layers and the recent stability of the West Antarctic ice sheet. *Nature* 264(5582): 152-155
Whillans I M 1979 Ice flow along the Byrd station strain network, Antarctica. *Journal of Glaciology* 24(90): 15-28
Young N W 1979 Measured velocities of interior East Antarctica and the state of mass balance within the I.A.G.P. area. *Journal of Glaciology* 24(90): 77-87
Young N W, Raynaud D, De Angelis M, Petit J-R, Lorius C 1984 Past changes of the Antarctic ice sheet in Adélie Land as deduced from ice core data and ice modelling (Abstract). *Annals of Glaciology* 5: 239