Antarctic Ice Core: CO_2 and Climatic Change Over the Last Climatic Cycle

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A deep ice core extracted at Vostok station, Antarctica, provides a record of atmospheric climate and CO_2 that is representative of global changes over the last glacial-interglacial cycle (160,000 years). Spectral analysis of the isotope temperature profile confirms the role of astronomical forcing in Quaternary climate changes. There is a remarkably close association between the climatic and CO_2 records. This association indicates a fundamental link between the climate system and the carbon cycle, although the processes involved are not clearly understood. A simple statistical comparison of the Vostok temperature record with various potential forcing factors suggests that CO_2 concentrations may have played a major role in the observed climatic record, in addition to insolation inputs exerted locally and at northern hemisphere latitudes (where continental ice sheets are growing and decaying at the glacial-interglacial time scale). We propose that CO_2 and other atmospheric chemical changes may have had an important effect on Quaternary climate by providing, for the large 100-kyr oscillation, the necessary amplification of the orbital forcing at that frequency.

Introduction

The recovery of environmental history is one of the keys to a better understanding of climatic changes caused either by natural processes or human influences. In this respect, studies of a few ice cores from Greenland and Antarctica have provided a great deal of globally significant information that reaches back continuously at least into the last glaciation, which culminated ~18,000 years ago. In these archives, the temperature of the atmosphere has been recorded by the isotope content of the snow, while its composition is preserved in air bubbles sealed off in the ice. The concentration of impurities incorporated into the ice depends on the precipitation (accumulation) rate and reflects the contribution of various natural and human sources, as well as the intensity of airborne transport.

After several attempts, the Soviet Antarctic Expeditions succeeded in drilling at Vostok station the deepest hole ever drilled in the ice. The hole extends back over 160,000 years, completely through the last glacial-interglacial cycle, and provides a record that is essentially undisturbed by ice flow conditions.

The Vostok Ice Core

Vostok station is located in the central part of East Antarctica (78°27′S and 106°51′E), at an elevation of 3490 m. The present mean annual temperature is −55.5°C, and the snow accumulation rate is about 2.3 g cm^{-2} yr^{-1}. The first drilling series reached a depth of 950 m in 1974. A new deep hole was started in 1980 and got down to 2083 m in 1982, with a later extension to 2200 m. The ice core chronology has been obtained [*Lorius et al.*, 1985] from a two-dimensional steady state glaciological model that is well suited to this area; it uses the known bedrock and surface profiles and accounts for changes in the rate of snow accumulation (see discussion below). The results indicate a rather regular increase of the age with depth, as shown in the scales of Figure 1. This is because the bottom of the core is far from the basal ice, where most of the perturbation of environmental records by ice flow and deformation occurs. The estimated accuracy is about 10–15 kyr at a depth of 2080 m for an age of 160 kyr. The time scale of the Vostok ice core thus obtained is independent of other paleoseries.

The Climatic Record

The existence of a relationship between the isotope composition (deuterium or ^{18}O) of the snow and the temperature of the site is well documented for polar areas. This type of relationship is the result of fractionation processes that take place during the atmospheric water cycle and is used as a basis for paleotemperature reconstruction. The validity of this kind of tool, particularly for deuterium in east Antarctic ice cores, is backed by various factors:

- The experimental linear isotope-temperature relationship is particularly well defined over this part of east Antarctica [*Lorius and Merlivat*, 1977], in which climatological conditions are relatively simple, and
- the observed slope (6‰/°C, expressed in δD‰ with respect to standard mean ocean water (SMOW), is in good agreement with

Cover. The Tennant Creek earthquakes of January 22, 1988, in the Northern Territory of Australia (epicenter at 19.8°S, 133.9°E), rank among the largest known Australian earthquakes. The U.S. Geological Survey's National Earthquake Information Service, Boulder, Colo., recorded magnitudes of M_s 6.3, M_s 6.4, and M_s 6.8. The earthquakes produced two thrust fault scarps whose combined length is about 30 km; such surface rupture is extremely rare in stable continental environments.

The surface rupture of the earthquakes had a devastating effect on vegetation near the scarp, but in a very selective manner. The view shown on the cover looks north across the main east-west thrust fault scarp (barely visible as the red ridge at the lower left). The two trees are Eucalypts (*E.* aff. *papuana*, "Central Australian Ghost Gun" form) and are about equidistant from the scarp. The dead Eucalyptus in the foreground is on the upthrown southern block, while the healthy background tree is on the footwall block. Other tree and shrub species also suffered, but Eucalyptus was the most vulnerable probably because of damage to its deep taproot by disruption of the upthrown block or actual shearing by the south dipping fault.

An early description of these events was given at the AGU Spring Meeting in May in Baltimore. The abstract is in *Eos*, vol. *69*, p. 400 [*Bowman et al.*, 1988]. A comprehensive report on these earthquakes is under preparation by Trevor Jones and his colleagues at the Australian Seismological Centre, Bureau of Mineral Resources, Canberra.

Species identification courtesy of L. A. S. Johnson, Royal Botanic Gardens, Sydney, Australia. Cover photo by Arch C. Johnston, Center for Earthquake Research and Information, Memphis State University, Tenn. For more information and pictures of the Tennant Creek earthquake, see "Fault Traces Australian Quakes," p. 682.

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0096-3941/88/6926-681$1.00

the value derived from a one-dimensional atmospheric isotope model [*Jouzel and Merlivat,* 1984].

The use of this figure for past conditions is justifiable after the fact because our estimate of the temperature change associated with the last deglaciation is consistent with values derived by independent approaches on the basis of ice crystal sizes [*Petit et al.,* 1987] and to a lesser extent with those of atmospheric model simulations [*Broccoli and Manabe,* 1987]. As discussed below, the derived snow accumulation history lends further support to this interpretation.

The continuous deuterium profile obtained from about 1500 samples is given in Figure 1, curve *a*, versus depth and time, with an indication of successive climatic stages (*A* to *H*). The record shows [*Jouzel et al.,* 1987] the existence of two interglacials (*A* — the current Holocene — and *G*). The last ice age is characterized by three minima, separated by slightly warmer episodes. The discovery of the existence of the previous ice age *H* proves that the profile covers the last entire climatic cycle. The derived surface temperature changes (Figure 1, curve *b*) were obtained from the isotope record after correcting for isotopic changes in the seawater (Figure 1, curve *c*). The amplitude of Antarctic climatic changes during deglaciations is of the order of 10°C, a figure that does not take into account a possible influence of surface altitude changes with time caused by changes in ice flow and ice thickness.

The Vostok record can be considered to be representative of a large polar area, as indicated by the very good agreement between three isotope profiles available over the last 40 kyr both from west (Byrd, *Johnsen et al.* [1972]) and east (Dome C [*Lorius et al.,* 1979] and Vostok) Antarctic ice cores. In fact, the main features of the Vostok climatic record are of global significance, at least qualitatively speaking. This significance is suggested by the comparison with the marine $\delta^{18}O$ record (Figure 1, *c*) of *Martinson et al.* [1987], who had meant to represent essentially global continental ice volume changes. The two records correspond very closely down to 110 kyr B.P.. Further back, there is a discrepancy in the duration of the previous interglacial, which can probably be explained by the relative uncertainties of the two independent time scales.

In addition to this temperature record, the Vostok ice core has allowed evaluation of past accumulation (precipitation) changes. One approach is based on the fact that current accumulation rates in Antarctica are governed by the amount of water vapor circulating above the inversion layer. This amount of water vapor is itself controlled by temperature via the saturation vapor pressure [*Robin,* 1977]. By using the linear relationship between the atmosphere (above the inversion) and surface temperatures, the isotope-based temperature record can thus be used to estimate past accumulation. The results give

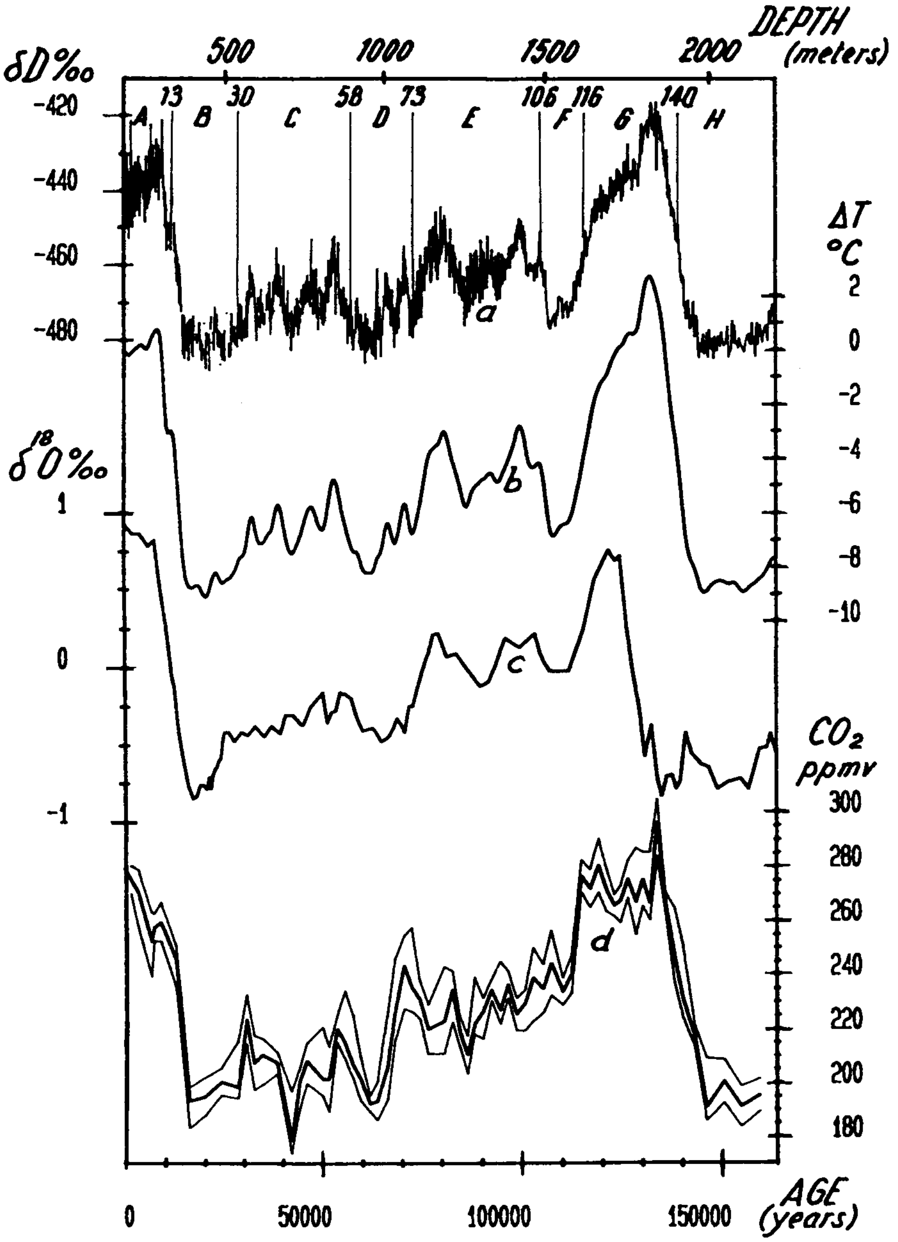

Fig. 1. Curve *a*: Vostok isotope profile (deuterium content per mille versus SMOW) with successive climatic stages *A* to *H* as defined by *Lorius et al.* [1985]. Curve *b*: Smoothed Vostok isotope temperature record expressed in degrees Celsius as a difference with respect to current surface temperature value [from *Jouzel et al.,* 1987]. Curve *c*: Marine $\delta^{18}O$ record from *Martinson et al.* [1986]. Curve *d*: CO_2 concentrations (ppmv). The best estimates are shown by the heavy line with the uncertainty bands on either side [from *Barnola et al.,* 1987]. The upper scale gives the depth of the Vostok ice core; the lower scale indicates the time (in years) of the various records.

New Information

Recent results from ice cores show that, as for CO_2, significant variations in atmospheric CH_4 concentration are associated with glacial-interglacial changes [*Stauffer et al.,* 1988; *Raynaud et al.,* 1988]. It is also suggested that paleo-aerosol concentration changes inferred from ice core studies have had a significant climatic impact [*Harvey,* 1988; *Legrand et al.,* 1988]. All these factors would induce temperature effects in the same direction as CO_2 and would then explain part of the amplification factor that is attributed only to CO_2 in this paper. There is then growing evidence that large chemical atmospheric modifications have contributed in glacial-interglacial climatic changes.

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May 1988

quite similar accumulation values during the two interglacials, while precipitation appears to have been reduced to about 50% of the current value during the coldest periods of the ice age. A second approach [*Yiou et al.*, 1985; *Raisbeck et al.*, 1987] is based on ^{10}Be measurements performed along the ice core. Concentrations of this long-lived cosmogenic radioisotope are quite similar during the two interglacials; they increase during colder periods, by up to a factor of 2 during full glacial conditions. If a constant ^{10}Be deposition flux is assumed, the measured concentrations reflect the amount of snow precipitation. Indeed, there is very good agreement between accumulation rates derived independently from the isotope temperature and rates from ^{10}Be records. The coherence of these results lends some support to this estimate of past precipitation and also indirectly lends further backing to the deuterium-temperature interpretation.

Although the past accumulation changes are directly related to Antarctic conditions, they are also of more general interest in that the growth and decay of ice sheets on a glacial-interglacial time scale largely depend on accumulation changes. The changes further illustrate the general trend of increased continental aridity conditions during the last glacial period [*Climate: Long-Range Investigation, Mapping, and Prediction (CLIMAP)*, 1981].

The Aerosol Record

The measurement of impurities along deep ice cores provides information on past aerosol loading and composition. These factors are relevant to climatic changes, although the relationship between atmospheric and snow concentrations is not very well documented. Comprehensive chemical analysis along the Vostok ice core, as reported by *De Angelis et al.* [1987] and *Legrand et al.* [1988], indicates a large increase of continental and, to a lesser extent, marine contributions (up to 30 and 5 times the current values, respectively) during full glacial conditions. These changes cannot be explained by changes in the rate of snow accumulation. The high glacial concentration values have been interpreted as the result of strengthened sources and transport linked to higher wind speeds (probably induced by higher temperature gradients with latitude), more extensive arid areas over the surrounding continents, and the greater exposure of continental shelves due to a lower sea level. More generally, marine and terrestrial aerosol concentrations measured in ice are strongly dependent on climatic conditions of global (source strength and atmospheric transport efficiency), regional (sea ice extent), and local (rate of snow accumulation) concern. In contrast to marine and terrestrial inputs, acidic gas-derived impurity concentrations (HNO_3, H_2SO_4) remain rather stable over the whole climatic cycle [*Legrand et al.*, 1988], indicating no long-term correlation between climate and volcanic activity.

The CO_2 Record

Atmospheric CO_2 data obtained both from Greenland and Antarctic ice cores over the last few years have shown that concentrations during the last glacial maximum were lower than Holocene values by 25–30% and that the last deglaciation was characterized by a concentration increase from ~190–200 to 270–280 parts per million by volume (ppmv) [*Delmas et al.*, 1980; *Neftel et al.*, 1982].

The Vostok ice core made it possible to extend the record of past atmospheric CO_2 right through the glacial-interglacial cycle [*Barnola et al.*, 1987]. Measurements performed at 66 different depth levels are separated by time intervals ranging from ~2 to 4.5 kyr. Because of the gradual enclosure of atmospheric air in ice, air extracted from the core is younger than the age of the snow deposit. This difference, which ranges from 2.5 to 4.3 kyr depending on climatic conditions, has been taken into account in establishing the CO_2 time scale. The best estimates of the CO_2 concentrations are plotted (Figure 1, curve *d*) together with the associated uncertainty bands. A smooth CO_2 profile is given in Figure 2, curve *a*.

The CO_2 concentration exhibits two very large changes between two levels that are centered near 190–200 and 260–280 ppmv, with the low and high values associated with full glacial and interglacial conditions, respectively. The high level is comparable with the so-called "pre-industrial" CO_2 concentration that prevailed some 200 years ago. There is a remarkable correlation (r^2 = 0.79) between the Vostok CO_2 and temperature records (Figure 2, *a* and *b*). In fact, these results provide the first direct evidence of a close association between atmospheric CO_2 and climatic (temperature) changes on a glacial-interglacial

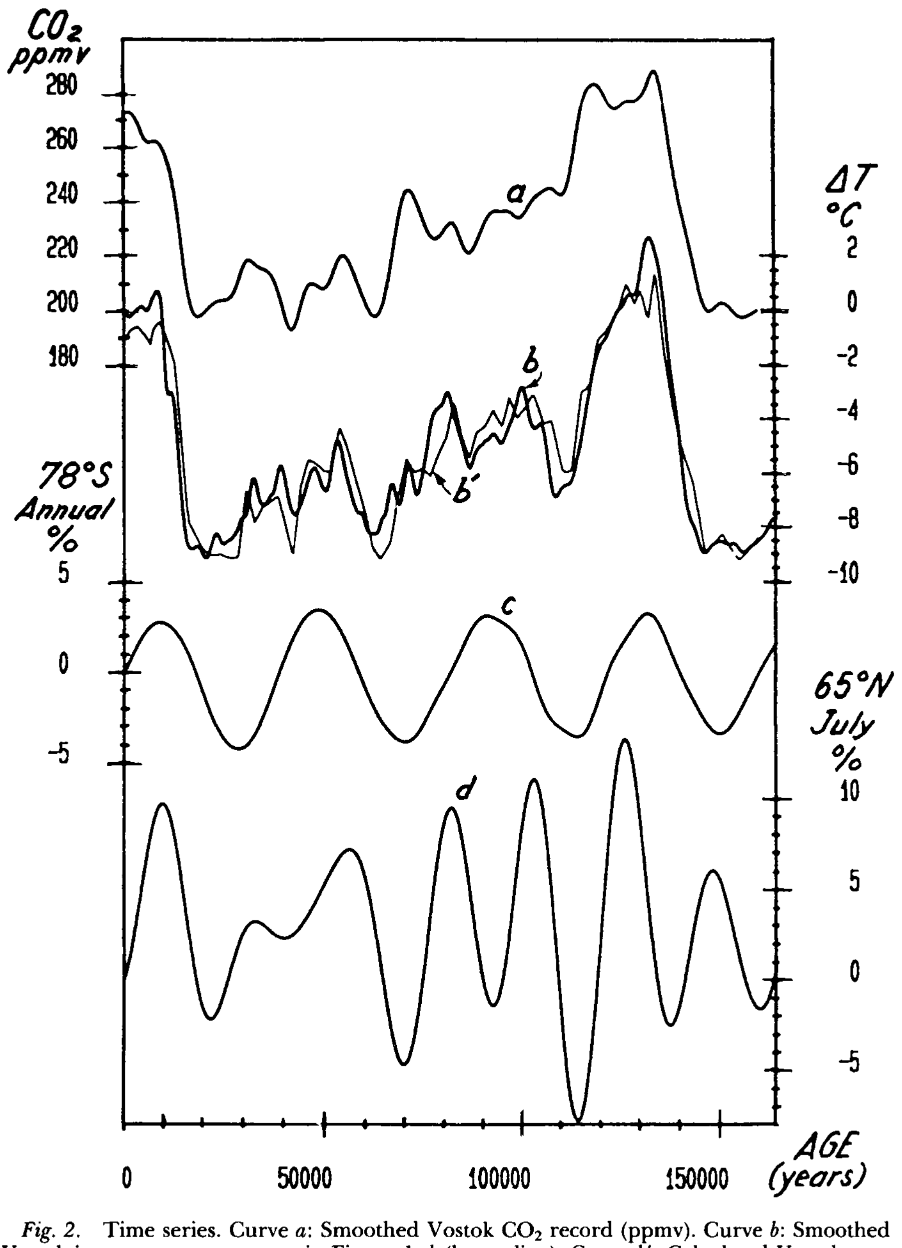

Fig. 2. Time series. Curve *a*: Smoothed Vostok CO_2 record (ppmv). Curve *b*: Smoothed Vostok isotope temperature as in Figure 1, *b* (heavy line). Curve *b'*: Calculated Vostok temperature changes from 78°S annual insolation, 65°N July insolation, and atmospheric CO_2 inputs (light line) [from *Genthon et al.*, 1987]. Curve *c*: Annual insolation at 78°S (Vostok station) expressed as the deviation in percentage from the current value [from *Berger*, 1978]. Curve *d*: July insolation at 65°N expressed as the deviation in percentage from the current value [from *Berger*, 1978].

time scale. Nevertheless, some differences are observable between the two records. There is, for instance, no very low CO_2 value associated with the rather cold stage shown near 110 kyr B.P. Furthermore, available data suggest that CO_2 and temperature vary simultaneously from glacial to interglacial, while during the transition from the previous interglacial to the last ice age (and also around 75 kyr B.P.) the CO_2 change clearly lags behind the climatic record.

These results also suggest that different mechanisms must be involved in these different modes of climate and carbon cycle interaction. This very important and unresolved question concerning the processes that control long-term atmospheric CO_2 concentration will not be discussed in detail here (see *Barnola et al.* [1987] and other references in this article). Although a possible influence of shallow ands deep modes of ocean circulation has been suggested, it is clear that other mechanisms (particularly involving the biological components of the global carbon cycle and possibly sea ice) also must be considered.

Orbital Forcing, Atmospheric CO_2, and Climate

Over the past 2 decades, the astronomical theory of paleoclimates [*Berger,* 1988] and the Milankovitch hypothesis that the growth and decay of the great northern hemisphere ice sheets is controlled by the summer insolation at ~65°N has received considerable support, particularly from a thorough analysis of the $\delta^{18}O$ deep-sea record [*Hays et al.,* 1976; *Imbrie and Imbrie,* 1980]. However, the implied large amplification of this relatively weak forcing (the total insolation received by the planet has varied by less than 0.6% over the last 10^6 years), the observed dominant 100-kyr cycle, and the synchronized termination of major glaciations in the northern and southern hemispheres cannot easily be explained by this hypothesis. Developments in the theory of Pleistocene climates include the nonlinear response of ice sheets to orbital forcing [*Imbrie and Imbrie,* 1980; *Le Treut and Ghil,* 1983] and, more recently, a possible contribution of the CO_2 greenhouse effect to explain very different climatic conditions [*Shackleton and Pisias,* 1985; *Broccoli and Manabe,* 1987; *Saltzman,* 1987]. The Vostok atmospheric temperature and CO_2 records offer a unique opportunity to examine the link that exists between a climatic atmospheric time series and astronomical and CO_2 forcings.

Aside from the large ~100-kyr oscillation, visual inspection of the Vostok temperature record (Figures 1, m5a and 2, *b*) clearly shows a 40-kyr signal with four well-marked temperature minima. The minima are in good agreement with those of the total insolation received at the Vostok latitude (Figure 2, *c*), which is governed by the obliquity cycle (/ mn5T = 41 kyr). There are also similarities between the Vostok record and the 65°N July insolation (Figure 2, *d*), which plays a key role in the Milankovitch theory of ice ages and is largely influenced by precessional changes (T = 19 and 23 kyr).

A spectral analysis of the Vostok record [*Jouzel et al.,* 1987] largely confirms the visual qualitative approach. Aside from the 100-kyr oscillation, the temperature profile is dominated by a strong 40-kyr component and is also influenced, to a lesser degree, by a ~20-kyr signal. These results, obtained from an atmospheric temperature record, further support the role of astronomical forcing in Pleistocene glacial-interglacial cycles, which has already been convincingly demonstrated on the basis of deep-sea core sediment records.

These remarks suggest that the Vostok climate could partly be driven by atmospheric CO_2 concentration, as well as by orbital forcing exerted locally and through northern hemisphere insolation changes. *Genthon et al.* [1987] examined the possible relative influence of these various forcings by calculating the temperature signal obtained as a response to CO_2 and insolation forcings, using a simple linear multivariate analysis. In regard to CO_2, the implicit assumption is that atmospheric changes are part of the climatic forcing. This approach is very simplistic, of course. First, nonlinear interactions certainly exist between the different components of the climatic system. Second, the role of the ocean, which has probably played an important part in linking the northern and southern hemisphere climates, is not specifically taken into account. Neither are sea ice extent changes, which are also believed to have important climatic role. It would also be useful to explore a wider range of possible forcings, such as changes

- in the atmospheric optical depth [*Rasool and Schneider,* 1971] resulting from variations in the aerosol loading, as shown by the previously described Vostok record;
- in other trace gases concentrations [*Wang et al.,* 1986], which we hope will be obtained from air bubble analysis in ice;
- in the amount of cloud condensation nuclei linked to oceanic dimethylsulfide production, as suggested by *Charlson et al.* [1987].

We also realize that this calculation does not throw light either on physical mechanisms involved or on the "chicken and egg" (cause and effect) problems, but despite its simplicity and overall weakness, the linear multivariate analysis between climate and various forcing factors provides some interesting results that can be summed up as follows:

- The combination of CO_2 and of southern and northern hemispheres inputs can explain more than 90% of the Vostok temperature variance, as illustrated by comparing Figure 2, curves *b* and *2b′*.
- The relative contribution of CO_2 is generally above 50% and could therefore explain about half of the 10°C interglacial-glacial changes. Lower CO_2 contributions are obtained, however, when we use the ice volume record (Figure 1,*c*) rather than the 65°N insolation (Figure 2, *d*) for northern hemisphere input.

Qualitatively, these results agree with the findings of *Broccoli and Manabe* [1987]. By using an atmosphere-ocean model, they found that low CO_2 concentration was the main cause of last glacial maximum equilibrium conditions in the southern hemisphere.

This CO_2 contribution is much higher than would be expected from the direct radiative effect of the CO_2 glacial-interglacial changes, which would only account for less than ~0.6°C. Indeed, the CO_2 amplification (that is, the ratio of the CO_2 temperature effect derived from the multivariate analyses to that corresponding to this direct radiative forcing) is higher than 5. This could imply that the CO_2 radiative forcing was strongly amplified over the last climatic cycle by climatic feedbacks. The existence of climatic feedbacks is documented by climatic simulations. Feedback factors deduced from CO_2 experiments with general circulation models of the atmosphere are well below the range cited above (2–4; see *Hansen et al.* [1984]). However, these experiments, which were carried out with modern boundary conditions, only account for fast processes (water vapor, cloud and sea ice). The extent of land ice and sea ice was larger during glacial conditions; hence climate sensitivity should have been higher at that time than during interglacials [*Hansen et al.,* 1984]. This could have caused an increase of the total feedback [*Genthon et al.,* 1987], leading to values in the range deduced from our multivariate analysis. A high-latitude CO_2 amplification effect has been also suggested from modeling studies [*Broccoli and Manabe,* 1987].

An important characteristic of the spectral CO_2 record is that in addition to the 100-kyr signal, this record shows a variance concentration around 20 kyr [*Barnola et al.,* 1987]. Beyond significant implications for understanding the modifications of the carbon cycle, this evidence suggests that astronomical forcing is involved in both temperature and CO_2 changes, although the role of this process is complex and not yet understood.

Nevertheless, the close correlation between CO_2 and temperature records and their spectral characteristics support the idea that climatic changes could be triggered by an insolation input, with the orbital forcing strongly amplified by CO_2 changes that are possibly induced orbitally. In particular, these results suggest that the 100-kyr glacial-interglacial oscillation may be related to the observed large CO_2 variations and not only to postulated nonlinearities in ice sheet growth and decay forced by insolation changes. This interpretation can only be considered tentative until it is backed by a clear understanding of the physical mechanisms involved. In any case, the results obtained from the Vostok ice core are convincing indications that there is an interactive link between orbital forcing, CO_2, and climate, and we support *Sundquist* [1987] in his suggestion that further progress will require that climate and the carbon cycle be treated as part of the same global system rather than as separate entities. We also believe that further deep ice core drilling and studies will contribute to this progress.

Acknowledgments

This work was supported in France by several institutions (Terres Australes et Antarctiques Françaises, Centre National de la Recherche Scientifique/Institut National des Sciences de l'Univers and Commissariat á l'Energie Atomique and in the Soviet Union by the Arctic Research Institute. Our research is based on a drilling program that was carried out by Soviet Antartic Expeditions. We are also grateful to the Division of Polar Programs, U.S. National Science Foundation, which provided logistic support.

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