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Vostok ice core provides 160,000-year record of atmospheric CO_2

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Direct evidence of past atmospheric CO_2 changes has been extended to the past 160,000 years from the Vostok ice core. These changes are most notably an inherent phenomenon of change between glacial and interglacial periods. Besides this major 100,000-year cycle, the CO_2 record seems to exhibit a cyclic change with a period of some 21,000 years.

ALTHOUGH the first direct CO_2 measurements in the atmosphere were made in the second half of the nineteenth century, atmospheric CO_2 variations have been monitored in a systematic and reliable manner only since 1958. Fortunately, nature has been taking continuous samples of the atmosphere at the surface of the ice sheets throughout the ages. This natural sampling process takes place when snow is transformed into ice by sintering at the surface of the melt-free zones of the ice sheets, with air becoming isolated from the surrounding atmosphere in the pores of the newly formed ice. After pore closure the gas remains stored in the ice moving within the ice sheet. During this natural air sampling and storage process, different mechanisms could alter the original atmospheric composition[1,2]. But by choosing appropriate sampling sites, ice cores (for example see ref. 1) and experimental methods[3], past CO_2 changes in the atmosphere can be determined with high confidence by analysing the air enclosed in the pores of the ice.

Previous results from ice-core analysis have already provided important reliable information on the 'pre-industrial' CO_2 level and the recent CO_2 increase induced by anthropogenic activities[4-6]. Striking CO_2 changes have also been detected in this way in the ice record covering the last 30-40 kyr[7-10], including the large CO_2 increase associated with the climatic shift from the Last Glacial Maximum (~18 kyr BP) to the Holocene.

Because of the extremely low temperatures at Vostok (present-day mean annual temperature is −55.5 °C) and the good core quality, the 2,083-m-long ice core recovered by the Soviet Antarctic Expeditions at Vostok (East Antarctica) provides a unique opportunity to extend the ice record of atmospheric CO_2 over the last glacial-interglacial cycle back to the penultimate ice age about 160 kyr ago[11]. Over this timescale a high correlation is found between CO_2 concentrations and Antarctic climate, with significant oscillatory behaviour of CO_2 between high levels during interglacial and low levels during glacial periods. The CO_2 record also seems to exhibit a cyclic change with a period of ~21 kyr, that is, around the orbital period corresponding to the precession.

Experimental procedure

Gas extraction and measurements were performed with the 'Grenoble analytical setup' described by Barnola *et al.*[12]. The

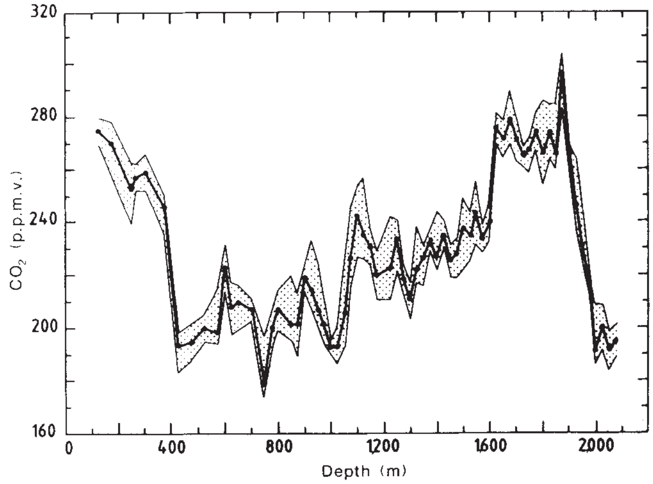

Fig. 1 CO_2 concentrations (p.p.m.v.) plotted against depth in the Vostok ice core. The 'best estimates' of the CO_2 concentrations are indicated by dots and the envelope shown has been plotted taking into account the different uncertainty sources.

method is based on crushing the ice under vacuum without melting, expanding the gas released during the crushing in a pre-evacuated sampling loop, and analysing the CO_2 concentrations by gas chromatography.

The analytical system, except for the stainless steel container in which the ice is crushed, is calibrated for each ice sample measurement with a standard mixture of CO_2 in nitrogen and oxygen. The corresponding accuracy (2σ) is evaluated from the standard deviation of the residuals corresponding to the calibration regression and ranges from 3 to 12 parts per million by volume (p.p.m.v.) for the measurements presented in this article.

We recently discovered an additional error due to our experimental system when a significant amount of water vapour is detected by the gas chromatograph. In such a case, selective CO_2 transport by water vapour (similar to that observed by Neftel *et al.*[4]) back to the ice crushing container is suspected of depleting the CO_2 from the air extracted from the ice and injected

Table 1 Mean CO_2 concentrations in Vostok ice core (best estimates and corresponding uncertainties, against depth and age)

Depth (m)	Age of the ice (yr BP)	Mean age of the air (yr BP)	CO_2 concentration (best estimate) (p.p.m.v.)
126.4 (Y)*	4,050	1,700	$274.5\mp^{5}_{5}$
173.1 (N)	5,970	3,530	$270.0\mp^{13}_{8}$
250.3 (N, N)	9,320	6,800	$252.0\mp^{13}_{10.5}$
266.0 (N)	10,040	7,500	$257.0\mp^{5}_{5}$
302.6 (N)	11,870	9,140	$259.0\mp^{7}_{7}$
375.6 (Y)	16,350	12,930	$245.0\mp^{10}_{5}$
426.4 (N)	20,330	16,250	$193.0\mp^{10}_{5}$
474.2 (N)	24,280	20,090	$194.5\mp^{7}_{7}$
525.1 (Y)	28,530	24,390	$200.0\mp^{5}_{5}$
576.0 (A)	32,680	29,720	$198.0\mp^{4}_{17}$
602.3 (Y)	34,770	30,910	$223.0\mp^{9}_{9}$
625.6 (N)	36,600	32,800	$207.0\mp^{10}_{10}$
651.6 (Y)	38,600	34,870	$210.0\mp^{11}_{5}$
700.3 (N)	42,320	38,660	$207.0\mp^{4}_{4}$
748.3 (A)	45,970	42,310	$178.5\mp^{5}_{18}$
775.2 (Y)	48,000	44,350	$200.0\mp^{10}_{5}$
800.0 (N, Y, Y)	49,850	46,220	$207.7\mp^{8.4}_{6.6}$
852.5 (A)	53,770	50,150	$201.0\mp^{6}_{19}$
874.3 (N)	55,450	51,770	$201.0\mp^{12}_{12}$
902.2 (N)	57,660	53,860	$219.5\mp^{5}_{10}$
926.8 (A)	59,670	55,780	$214.5\mp^{6}_{19}$
951.9 (A)	61,790	57,800	$206.5\mp^{5}_{18}$
975.7 (Y)	63,880	59,770	$201.0\mp^{8}_{8}$
1,002.5 (N)	66,230	62,080	$192.0\mp^{3}_{3}$
1,023.5 (N)	68,040	63,960	$193.0\mp^{7}_{7}$
1,052.4 (A)	70,470	66,540	$205.5\mp^{12}_{20}$
1,074.8 (A)	72,330	68,490	$226.5\mp^{11}_{19}$
1,101.4 (Y)	74,500	70,770	$243.0\mp^{16}_{11}$
1,124.2 (A)	76,330	72,690	$235.0\mp^{9}_{22}$
1,148.7 (Y)	78,270	74,720	$230.5\mp^{7}_{7}$
1,175.0 (N)	80,320	76,860	$219.5\mp^{9}_{9}$
1,225.7 (A)	84,220	80,900	$222.5\mp^{12}_{20}$
1,251.5 (N)	86,220	82,920	$234.0\mp^{12}_{7}$
1,274.2 (Y, N)	87,980	84,700	$218.8\mp^{5.5}_{5.5}$
1,299.3 (N)	89,940	86,680	$210.0\mp^{7}_{7}$
1,322.5 (A)	91,760	88,520	$221.5\mp^{4}_{17}$
1,349.0 (N)	93,860	90,630	$226.0\mp^{10}_{5}$
1,374.8 (Y)	95,910	92,700	$234.0\mp^{4}_{4}$
1,402.5 (A)	98,130	94,940	$226.5\mp^{5}_{18}$
1,425.5 (Y)	100,000	96,810	$236.0\mp^{5}_{5}$
1,451.5 (N)	102,210	98,950	$225.0\mp^{6}_{6}$
1,476.1 (N)	104,410	101,040	$229.0\mp^{10}_{5}$
1,499.6 (Y)	106,610	103,130	$238.5\mp^{16}_{11}$
1,526.3 (N)	109,240	105,620	$234.5\mp^{9}_{9}$
1,547.0 (Y)	111,250	107,650	$244.0\mp^{12}_{12}$
1,575.2 (N)	113,850	110,510	$233.5\mp^{5}_{5}$
1,598.0 (N)	115,850	112,700	$240.0\mp^{10}_{7}$
1,626.5 (Y)	118,220	115,290	$276.0\mp^{6}_{6}$
1,651.0 (Y, N)	120,170	117,410	$271.5\mp^{7}_{7}$
1,676.4 (N)	122,100	119,500	$280.0\mp^{10}_{10}$
1,700.9 (N)	123,900	121,430	$271.0\mp^{8}_{8}$
1,726.8 (N, N)	125,730	123,380	$265.3\mp^{4}_{4}$
1,747.3 (Y, N)	127,150	124,880	$267.0\mp^{8}_{5}$
1,774.1 (N)	129,020	126,770	$275.0\mp^{7}_{7}$
1,802.4 (A)	131,030	128,780	$266.5\mp^{12}_{10}$
1,825.7 (Y, N)	132,700	130,460	$275.0\mp^{10}_{10}$
1,850.5 (A)	134,510	132,280	$266.0\mp^{6}_{19}$
1,875.9 (Y)	136,450	134,170	$296.5\mp^{13}_{8}$
1,902.0 (Y)	138,660	136,170	$266.0\mp^{4}_{4}$
1,928.0 (A)	141,170	138,410	$246.5\mp^{10}_{18}$
1,948.7 (A)	143,440	140,430	$231.0\mp^{7}_{20}$
1,975.3 (N)	146,860	143,370	$217.0\mp^{4}_{4}$
1,998.0 (A)	150,330	146,340	$191.0\mp^{5}_{18}$
2,025.7 (N)	154,980	150,700	$200.5\mp^{8}_{8}$
2,050.3 (N, N)	159,100	154,970	$191.3\mp^{7.5}_{7.5}$
2,077.5 (N)	163,670	159,690	$195.5\mp^{6}_{6}$

* (Y) indicates the presence and (N) the absence of an H_2O peak in the chromatographic analysis. Ambiguous cases are denoted (A).

into the gas chromatograph. Experiments indicate that the presence of water vapour in the analysed air is not systematic but, when it occurs, leads to measured CO_2 concentrations lower by about 13 p.p.m.v. than in its absence. For the 75 Vostok core measurements reported in this paper, we found 22 cases with a water-vapour peak and 37 cases without. The presence of this peak was ambiguous for the 16 remaining measurements, leading in those cases to an additional uncertainty. Another source of uncertainty lies in the fact that two different stainless steel containers were used for ice crushing and that the respective results differ statistically by about 5 p.p.m.v.

For each depth level our 'best estimate' of the CO_2 concentration takes into account the correction of +13 p.p.m.v. for the effect of water vapour where there were unambiguous water-vapour peaks. For consistency with previously published data obtained with the same experimental setup[5,10,12] we added, when evaluating this 'best estimate', 5 p.p.m.v. to the CO_2 concentrations measured with the crushing container giving statistically lower values.

All the identified sources of uncertainty (experimental accuracy, effects of water vapour and crushing container) have been taken into account in plotting the CO_2 envelope shown in Fig. 1 and lead to errors around the 'best estimates' ranging from +3 to +22 p.p.m.v. on the positive side and from −3 to −16 p.p.m.v. on the negative side (Table 1). A single measurement was generally performed on each of the 66 depth levels investigated. Eight levels were nevertheless sampled and measured 2 or 3 times. For these levels the scatter of the multiple measurements is generally much smaller than the width of the envelope.

Although we are confident in the relative CO_2 variations measured, a systematic error could affect the absolute values. A recent comparison, still in progress, between results from the Physics Institute of Bern and our laboratory indicates that the values measured in Bern are systematically higher by about 10 p.p.m.v. The results of the comparison, when completed, will be published jointly by the two groups elsewhere.

Vostok CO_2 record

Dating the air found in ice bubbles. Dating the successive ice layers at Vostok has been discussed and an ice chronology established by Lorius *et al.*[11]. This ice chronology cannot, however, be directly applied to the dating of the CO_2 record. Indeed, owing to the air enclosure process in the ice, the air is isolated from the atmosphere in the firn layers well after the precipitation has been deposited at the surface of the ice sheet, and consequently air extracted from the ice is younger than the ice itself.

The following assumptions have been made to date the air in relation to the ice: (1) the air in the firn layers is well mixed with the atmosphere until firn pores close; (2) pore closure occurs roughly in the firn density interval 0.80–0.83 (ref. 13), that is, in the deepest layers of the firn (found between about 86 and 96 m depth at Vostok); and (3) the density-depth profile has remained unchanged over the past 160 kyr.

Based on these assumptions the difference between the age of the ice and the mean age of the air, which is dependent on accumulation rate, is evaluated taking into account the temporal changes of the accumulation rate[11]. This calculated difference varies between about 2,500 yr for the warmest to about 4,300 yr for the coldest periods.

On the other hand, all the air enclosed in an ice sample has not been pinched off from the atmosphere at the same time but rather pore after pore over a time interval which, with the above assumptions, lies between 300 and 750 yr. This acts as a low-pass filter and means that each CO_2 measurement represents roughly an average value over several hundred years.

All the CO_2 ages given in this paper are based on the ice

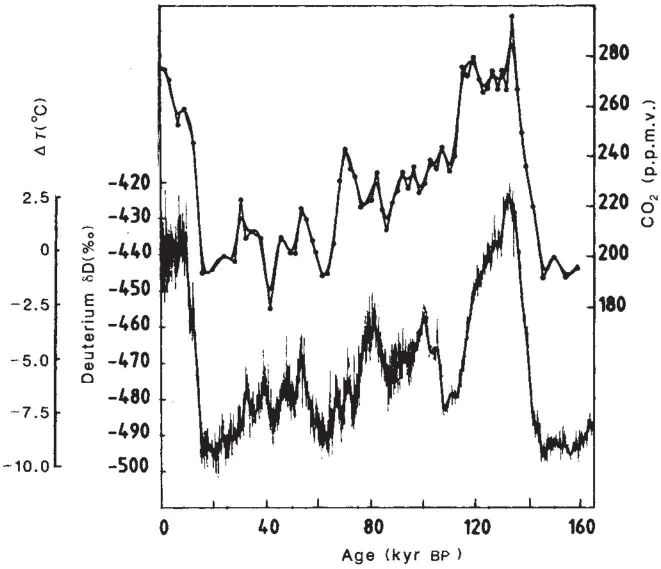

Fig. 2 CO_2 concentrations ('best estimates') and smoothed values (spline function) in p.p.m.v. plotted against age in the Vostok record (upper curves) and atmospheric temperature change derived[14] from the isotopic profile (lower curve). The deuterium scale corresponds to values after correction for deuterium changes of oceanic water[14].

chronology given by Lorius *et al.*[11], and dating of the air relative to the ice was done as described above. No better quantitative method is currently available to evaluate the age of the air. Nevertheless the two first assumptions made above probably lead to a maximum difference between the two ages (air and ice)[5], whereas the last would lead to an age difference too small (by maybe several hundred of years) for the coldest periods.

Description. Sixty-six depth levels were investigated for CO_2 measurements along the 2,083-m core. They are spaced every ~25 m from 850 m depth to the bottom. Because of the presence of fractures in the upper part of the core, the spacing is generally larger above 850 m depth. With this sampling, the mean age difference between two neighbouring levels ranges from ~2,000 to ~4,500 yr.

The record covers the past ~160 kyr and includes the following major climatic periods: the Holocene, the last glaciation, the previous interglacial and the end of the penultimate glaciation[11,14]. Figure 1 shows the results (best estimates and envelope obtained as described above) plotted against depth. Figure 2 shows the CO_2 variations with age of the air.

The CO_2 record exhibits two very large changes, one near the most recent part of the record (~400 m depth or 15 kyr BP) and the other near the earliest part of the record (~1,950 m depth or 140 kyr BP), between two levels centred on 190-200 and 260-280 p.p.m.v. roughly typical of the lowest and highest values of the whole record. The high level is comparable with the so-called 'pre-industrial' CO_2 level that prevailed roughly 200 years ago, just before the large anthropogenic disturbance of the CO_2 cycle; the low level ranges among the lowest values of the known geological history of carbon dioxide over the last 10^8 yr (ref. 15). These two large CO_2 changes correspond to the transitions between full glacial conditions (low CO_2) of the last and penultimate glaciations, and the two major warm periods (high CO_2) of the record: the Holocene and the previous interglacial.

Between these two extremities of the record, that is, over the period covering mainly the last glaciation, the CO_2 shows a general decreasing trend with the lowest values found over the last part of the glaciation (between ~1.025 and 425 m depth, or 65 and 15 kyr) and with two marked breaks: a first decrease of ~40 p.p.m.v. at ~1,610 m depth (~114 kyr BP), and a second of ~50 p.p.m.v. at ~1,070 m depth (~68 kyr BP). Other CO_2 changes are superimposed on the general decreasing trend, suggesting an oscillatory behaviour with an apparent period of ~20 kyr, especially between ~80 and 20 kyr BP. These changes are more pronounced in the last part of the glaciation, but note that some of the variability observed above 850 m depth could be due to the lower ice quality in that part of the core.

The fact that the record does not indicate a continuous long-term trend is an important result in itself regarding possible fractionation of the different gas components due to the interaction with the ice lattice and which should be reflected by such a trend. This adds confidence to the preservation of the atmospheric CO_2 record in the ice over such a long period.

Spectral analysis. The record, as shown in Fig. 2, suggests a cyclic behaviour of the CO_2 changes. Because of the potential link between CO_2 and climate, and consequently between CO_2 and astronomical cyclic forcing of climate, a spectral analysis of the CO_2 record has been done. For comparison with the δD record of Vostok (see below), the same procedure as in ref. 14 has been applied, using values equally spaced every 200 years and obtained by linear interpolation of our best estimates for CO_2 measurements. Because of the short length of the record (relative to the frequencies of interest), we combined different spectral techniques to extract reliable information. Blackman-Tukey (BT) and maximum entropy (ME) methods with and without prewhitening were applied. The BT method has a poor resolution but well defined statistical properties; the use of the ME method increases the frequency resolution but the amplitude estimate has to be interpreted with caution[16]. The prewhitening allows the removal of part of the variance at low frequencies and a more detailed picture in the tilt and precession frequency bands. The ME spectra shown in Fig. 3 were obtained with the Barrodale and Eriksson algorithm[17].

The spectra obtained with the unprewhitened series are dominated by the 100-kyr components (116 kyr for the ME peak). The BT spectrum (not shown in Fig. 3) is relatively flat for higher frequencies but shows a significant bump for periods between 25 and 20 kyr. The ME spectrum indicates a concentration of variance in this frequency band with a well-defined peak at 21 kyr; it also displays a peak at ~55 kyr. Prewhitening, which gives more detailed information for this part of the spectrum, confirms the position of a 21-kyr peak (21.0 kyr for ME). Sensitivity analysis shows the remarkable stability of this peak ($\sigma =$ 0.1 kyr) with respect to the lag value (BT) or to the autoregressive order (ME). The ME prewhitened CO_2 spectrum is thus dominated by this component of ~21 kyr and also shows a secondary peak at ~40 kyr (43.1 kyr). As the latter may result from the variance transfer of the 55-kyr peak mentioned above (unprewhitened ME spectrum), it must be interpreted very cautiously.

Because of the relatively small number of measurements with corresponding errors, any interpretation of the spectral analysis needs to be cautious. To check the significance of the spectrum results we have performed some tests with random curves placed within the error band. The results show a rather good stability of the peaks, especially for 21 kyr (20.9 ± 0.2). Some implications of this CO_2 spectrum on the CO_2-climate correlation and on the CO_2 cycle are discussed below.

Comparison with other ice records. Several ice cores from Antarctica and Greenland have already shown CO_2 variations over the past 30-40 kyr (D 10 (ref. 7), Dome C[7,10], Byrd[8] Camp Century[8], Dye 3 (refs 9, 18)). The Vostok profile is in good agreement with the general common features of these records, which show low CO_2 values (~200 p.p.m.v.) during the Last Glacial Maximum (~18 kyr BP) and an increase of the atmospheric CO_2 associated with the glacial-Holocene transition.

Other striking individual CO_2 features are also observed in some of these previous ice records. For instance, abrupt CO_2 changes are recorded in the Dye 3 core between 30 and 40 kyr BP (ref. 9) and in the Dome C core near the end of the glacial-Holocene transition[7,10]. They do not appear in the measured

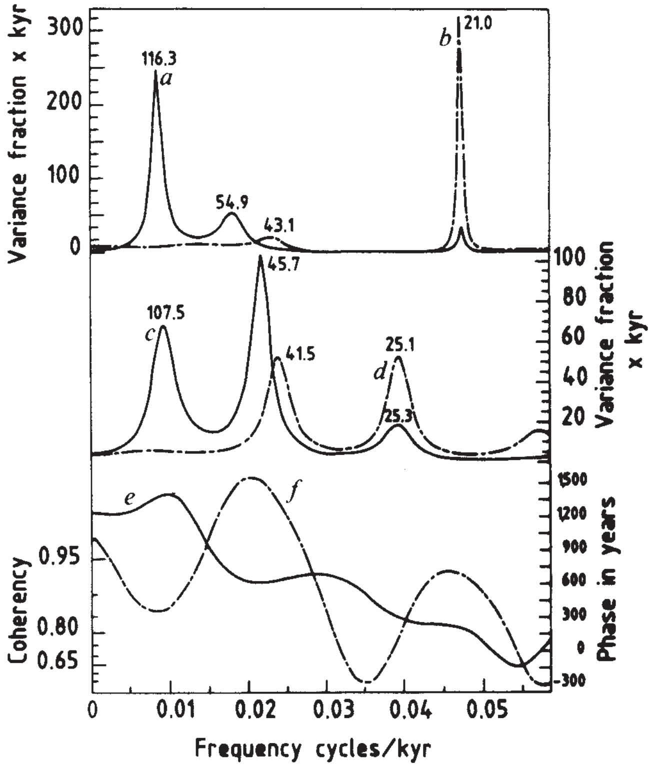

Fig. 3 *a, b,* Variance spectra of the Vostok CO_2 record. The normalized variance density is plotted against frequency in cycles per kyr. The continuous line (*a*) refers to the original series and the dashed line (*b*) to the series after prewhitening by a first-order difference filter. The spectra were obtained by the ME method applying the Barrodale and Ericksson algorithm with an autoregressive order of 40%. *c, d,* Variance spectra of the Vostok isotope temperature record from ref. 14, obtained with the same procedure. *e, f,* Cross-spectral analysis between CO_2 and temperature for coherency (*e*) and phase spectrum (*f*), obtained by applying the Blackman-Tukey method. The phase (right scale) is positive when CO_2 lags the temperature.

Vostok profile, but our sampling does not allow the search for such rapid changes; furthermore, the low-pass filter effect of the air-trapping process (mentioned above) may prevent any detection in the Vostok core of the changes observed in the Dye 3 core. Note also that the high CO_2 level (>270 p.p.m.v.) observed in the Dome C core between 23 and 30 kyr BP is not found in the Vostok record. These high CO_2 values could be due to the poor quality of the Dome C ice in this part of the core[19].

Thus, taking into account the resolution of the different records, the Vostok CO_2 results are consistent with the other ice records already published, covering only the most recent part of the time interval revealed by the Vostok core.

Comparison with deep-sea sediment record. $\delta^{13}C$ differences between planktonic and benthic foraminifera found in a deep-sea core (V 19-30) have been used by Shackleton *et al.*[20] to deduce a record of atmospheric CO_2 covering approximately the last climatic cycle and by Shackleton and Pisias[21] to extend this record over the past 340 kyr. The basic idea, following an approach developed by Broecker[22], is that a $\delta^{13}C$ difference between ocean surface and deep waters is associated with the removal of carbon from the surface by photosynthesis and consequently with the atmospheric CO_2 concentration level. The CO_2 record thus obtained agreed fairly well with the available CO_2-ice record, that is, corresponding to the period covering the past ~40 kyr.

We are now able, with the Vostok ice record, to extend the comparison over the past ~160 kyr. For this comparison we use the more recent data by Shackleton and Pisias[21] for the marine record. Major similarities in the general trends are observed. Both records show rapid and large increases of CO_2 concentrations associated with the two deglaciations and exhibit the highest CO_2 values during the interglacial periods. They also show together a relatively abrupt CO_2 decrease associated with the beginning of the last glaciation.

The comparison is limited in detail because of differences in timescales[14] and in time resolutions between the ice and marine records. There are nevertheless significant differences between the two curves, which include the following observations.

(1) The disparity between previous interglacial and Holocene CO_2 values is much smaller in the Vostok record.

(2) The CO_2 concentrations deduced from the marine record approach Holocene levels several times during the last glaciation, unlike the Vostok record.

(3) The morphology of the Vostok CO_2 curve over the last glaciation (that is, over a large common part of the two records) is definitely not the same as that of the V 19-30 curve. Thus the general CO_2 decrease observed in the Vostok core does not appear in the marine record and the most striking change appears in the Vostok curve as a marked CO_2 decrease (between ~71 and 62 kyr BP in the Vostok timescale) and in the V 19-30 record as a large and sharp CO_2 increase (between ~60 and 55 kyr BP in the V 19-30 timescale).

(4) Spectral analysis has been done[21,23] on the CO_2 record recovered from the marine core study. The V19-30 spectrum exhibits peaks around all the orbital periods (~100 kyr for the Earth's eccentricity, ~41 kyr for the obliquity of the Earth's axis and 23 and 19 kyr for the precession of the equinoxes), whereas the Vostok spectrum shows as mentioned above, aside from the 110 kyr period, a peak at ~21 kyr but nothing clearly corresponding to the obliquity frequency. The comparison is, in fact, not straightforward because the record lengths (~340 kyr for V19-30 and ~160 kyr for Vostok) as well as part of the procedures used for the spectral analysis are different. We have checked the possible influence of these differences by applying equivalent procedures to the Vostok record and to the V19-30 data given in ref. 21, limited to the past 160 kyr. The V19-30 spectrum still shows, in contrast with Vostok, a significant peak around the 40-kyr period.

Thus, although the CO_2 record derived from the carbon isotope differences ($\Delta\delta^{13}C$) between planktonic and benthic foraminifera found in the V19-30 core, as well as the Vostok CO_2 record, indicate that alternations of low and high mean CO_2 concentrations and of glacial and interglacial periods are related, there are significant discrepancies between the changes observed in each of the records. Since the ice record provides *a priori* a more direct and accurate measurement of atmospheric CO_2 changes, these differences suggest that the $\Delta\delta^{13}C$ record of the V19-30 core cannot be interpreted as a pure atmospheric CO_2 curve.

Implications for climate

In this section we compare the CO_2 profile described above with the ice isotopic record obtained on the same core[14] and discuss some climatic implications. A companion paper[24] addresses the potential role of various forcing factors, including CO_2, for producing the temperature record derived from the isotopic composition of the Vostok ice core.

The isotopic record shows the 'dramatic' changes between the two glaciations and the two interglacial periods and provides a detailed description of other climatic variations, especially during the last glacial and the previous interglacial periods.

Our CO_2 profile and the Vostok climatic record (adapted from ref. 14) are plotted together against time in Fig. 2. The climatic significance of the isotopic profile is fully discussed in refs 11 and 14 and high (low) δD values are associated with 'warm' ('cold') temperatures. The temperature scale refers to the atmospheric surface-temperature changes in the Vostok area. The CO_2

and δD records, as obtained from the same ice core, can be directly compared after allowing for the mean age difference between the ice and the air enclosed in the ice (see section on the dating); this age difference has been taken into account in Fig. 2.

The first obvious feature when comparing the two records is the marked similarity in temporal variations. The high correlation ($r^2 = 0.79$) between the linearly interpolated CO_2 curve based on the best estimates and the smoothed δD curve shown in Fig. 2 reflects that generally high (low) CO_2 concentrations correspond to 'warm ('cold') temperatures in the Vostok area. Thus the CO_2 values for the two interglacial periods (mean concentrations of 263 p.p.m.v. for the Holocene and of 272 p.p.m.v. for the previous interglacial period) are much higher than the concentrations measured in the glacial ice (on average 215 p.p.m.v.). Furthermore during the last glaciation, as mentioned above, the mean CO_2 level was higher during the first part (230 p.p.m.v. between 110 and 65 kyr BP) than during the second part (203 p.p.m.v. between 65 and 15 kyr), which also shows colder climatic conditions.

But a more detailed examination of the two records in Fig. 2 indicates differences:

(1) During the previous interglacial period and the transition towards the last glaciation, although both CO_2 and δD seem to peak simultaneously at ~135 kyr BP (note that the CO_2 peak is documented by only one depth level and therefore needs to be confirmed), the CO_2 record shows relatively high and constant values over at least the 10 kyr after the peak (see Fig. 2), whereas the δD curve clearly decreases over the same time interval. A similar effect, although less obvious, seems to appear around 75 kyr BP when the δD curve shows a decreasing trend whereas the average CO_2 apparently remains constant.

(2) The first 'isotopically cold' peak observed during the last glaciation, around 110 kyr BP, has no low-CO_2 companion peak.

The superposition of the CO_2 and δD records also provides information on the comparative timing of the most significant changes in the two signals. The sparse CO_2 sampling and to a smaller extent the uncertainties in the CO_2 measurements and on the age difference between the air trapped in the ice and the ice itself make the determination of a time difference between the two signals of Fig. 2 only possible for differences larger than 3500 yr. Within this uncertainty, the following trends are observed: (1) δD and CO_2 changes appear almost simultaneously when proceeding from glacial to interglacial conditions; (2) as noted above, the situation could be different when proceeding from the previous interglacial to the last glaciation with the CO_2 change clearly lagging behind the δD decrease.

Furthermore information on the comparison between the two time series can be inferred from the spectral analysis. As mentioned above, the CO_2 spectrum reveals a well-defined peak at 21 kyr and, with prewhitening, a relatively weak secondary peak at ~40 kyr that must be interpreted very cautiously. This contrasts (see Fig. 3) with the temperature spectrum deduced from the δD record and given by Jouzel *et al.*[14]. The temperature spectrum does indeed indicate peaks at ~40 and ~20 kyr (that is, which can be associated with the obliquity and precession cycles), with the 40-kyr peak dominating the 20-kyr. The results (Fig. 3) of the cross-spectral analysis for coherence and phase spectrum between CO_2 and temperature (δD) show high coherency in the orbital frequency band and indicate that CO_2 could lag the temperature slightly. This lag is not statistically significant but could reflect, as mentioned above, the temperature signal decreasing before the CO_2 when proceeding from the interglacial to the glacial period.

The above comparison deals with a CO_2 signal that should be of global atmospheric significance and a climatic signal that is *a priori* relevant to Antarctica and consequently to more local conditions. The Vostok δD record shows, in fact, important climatic changes on a worldwide scale[11,14]. In this more general context it is interesting to compare the CO_2 level measured over the previous interglacial with the present atmospheric CO_2 concentrations, because this period of the past has been proposed as an analogue for a future CO_2-warmed world. The Vostok results indicate a mean CO_2 concentration (272 p.p.m.v.) comparable with the 'pre-industrial' CO_2 level (estimated to be 275 ± 10 p.p.m.v. (ref. 25)). Furthermore, the CO_2 peak of about 300 p.p.m.v. found at ~135 kyr BP, if confirmed, is significantly lower than the current level of about 345 p.p.m.v.

The high correlation between atmospheric CO_2 and isotopic temperature found in the Vostok record suggests that the radiative effect of CO_2 coupled with associated feedback mechanisms appears to be a serious candidate as one of the driving forces behind the palaeo-temperature changes recorded in the Vostok core. The relative weights of different types of forcing in the reconstruction of the Vostok temperature variations are discussed in the companion paper[24]. This approach points out the probable importance of CO_2 in influencing the main feature of the climate during the last climatic cycle.

Examining the parts of the CO_2 and δD records containing the most pronounced changes, although the two transitions from glacial to interglacial conditions shown by the record indicate almost simultaneous changes for CO_2 and isotopic temperature, the situation is different when looking at the transition between the previous interglacial period and the last glaciation. As shown in Fig. 2, a large portion, about 7 °C, of the isotopic temperature decrease leading to the glacial conditions takes place between ~132 and 115 kyr, a time during which no significant CO_2 changes are observed. Our results thus indicate that climatic forcings other than CO_2 induced a large part of the temperature change over Antarctica linked with the interglacial-glacial transition. The marked CO_2 decrease (from ~275 to 235 p.p.m.v.) appears only during the final phase of the climatic cooling (between ~115 and 110.5 kyr) and is associated with a decrease of ~2 °C in the Vostok isotopic temperature.

Based on the above discussion, we suggest that the interactions between climate and CO_2 could be different depending on whether the climate shifts from glacial to interglacial or from interglacial to glacial conditions. In the latter case, orbital and orbitally derived forcing could have influenced the marked cooling trend in the Antarctic with a dominant contribution to the temperature decrease, before the potential climatic effect of the change in CO_2 concentrations. Note that the second (in terms of amplitude) cooling trend, found around 75 kyr BP in the Vostok record, exhibits a similar behaviour of the CO_2–δD comparative variation.

Implications for CO_2 cycle

As well as providing information on the CO_2-climate interaction, our CO_2 profile allows us to discuss the modifications of the carbon cycle during the last climatic cycle. Based on previous ice core results over the past 30-40 kyr, several models have been proposed to explain the increase of atmospheric CO_2 associated with the last deglaciation. Detailed descriptions of these models can be found in Broecker and Peng[26] or Berger and Keir[27]. These models are based on the idea that the biological productivity of the ocean controls the atmospheric CO_2 but they differ in the mechanisms driving these productivity variations.

In one family of models, sea-level variations are responsible for the atmospheric CO_2 changes[22,28]. The general trend of the Vostok CO_2 profile is similar to the benthic $\delta^{18}O$ records, which mainly reflect ice volume or sea level (for example see Fig. 2*b*, *e* of the companion paper[24]), making these models attractive. Berger and Keir[27] and Keir and Berger[29] attempt to model the past atmospheric CO_2 modifications due to sea level variations. Choosing appropriate parameters, the morphology of the derived CO_2 curve is close to that of the Vostok curve and the CO_2 variations lag the sea-level changes by ~1 kyr. To test this time lag, it is necessary first to evaluate the phase relationship between the CO_2 and the Vostok temperature and secondly between the Vostok temperature and the sea level. In deglaciations, as already mentioned, the CO_2 begins to increase almost simultaneously with the Vostok temperature. The precise timing between the temperature and the sea level is difficult to obtain because these two signals are not recorded in the same medium. It is nevertheless reasonable to assume that the sea level cannot increase before the Antarctic temperature, as suggested by the interpretation of the marine sediment record, which indicates that changes in Southern Hemisphere sea-surface temperature have generally led the changes in ice volume[30,32]. Although denser sampling would be required for a more definite conclusion, the Vostok results thus suggest that at the end of glaciations the CO_2 increased before the sea level and not after as predicted by the models mentioned. At the beginning of the last glaciation (~120 kyr BP), the CO_2 decreased ~10 kyr after the temperature and thus most probably after the sea-level change. Although this phase relation cannot exclude the influence of the sea level on the CO_2 variations during this period, it is important to note that the CO_2 decrease is very sharp (35 p.p.m.v. in 2 kyr) and seems incompatible with the mechanisms involved in the models proposed. We suggest that this abrupt change of the atmospheric CO_2 between two nearly constant values could be due to an abrupt modification of the deep oceanic circulation possibly linked with the sea-level decrease. Such rather rapid circulation changes associated with climatic transitions have been shown to occur[33].

In another family of models, changes in oceanic circulation affect the biological productivity of the surface ocean and thus the atmospheric CO_2 concentration. These models stress changes occurring in the high latitude deep-water formation areas[34-36] and in the upwelling zones at low latitudes[35]. The spectral analysis of the Vostok CO_2 record shows, as well as the 110-kyr component, a very weak and doubtful 41-kyr and a clear 21-kyr peak. This feature can give some indications of the latitudes involved in the forcing of the atmospheric CO_2. The latitudinal variation of the insolation spectra is complex. Although the presence of an obliquity component (41 kyr) seems to be a characteristic of high latitudes, this component is negligible around the equinoxes and becomes important around the solstices[37]. From marine proxy data, the spectral analysis of the sea-surface temperature of the North Atlantic shows that, apart from the 110-kyr component, the 41-kyr component is dominant for latitudes greater than 45° N (ref. 38), and we can note that the Vostok temperature profile also exhibits a strong 41-kyr period[14]. The quasi-absence of a 41-kyr period in the CO_2 record could thus suggest that the high latitudes do not have a major influence on the CO_2 variations. Nevertheless we cannot exclude an influence of these latitudes during part of the year, in particular around the equinoxes.

At low latitudes, upwelling areas are known to play a key role in the total biological productivity of the oceans and may thus influence the atmospheric CO_2 significantly. Evidence exists from the reconstructed sea-surface temperatures that upwellings were stronger during the Last Glacial Maximum (18 kyr BP)[39]. Similar conclusions are obtained from the palaeoreconstructions of trade-wind strength[40-42], responsible for the upwelling currents. Some of these indicators exhibit similarities with the atmospheric CO_2, for instance at the end of the two last glaciations the upwelling productivity off the NW African coast decreased before the increase in sea level[40], as did the winter trade-wind speed near the Peru coast[41]. Note also that the upwelling productivity off NW Africa was high during only the second part of the glaciation, that is, between ~70 and 15 kyr BP[41], and that the Vostok aluminium concentration profile exhibits three very pronounced spikes suggesting stronger atmospheric circulation at ~150, ~70 and ~20 kyr BP[43]. These spikes correspond to very low CO_2 values (~200 p.p.m.v.).

All these facts suggest that atmospheric circulation, coupled with oceanic circulation, at least through the upwelling currents, could have played an important role in past CO_2 variations. This influence may have been especially important between 70 and 15 kyr BP and thus could be responsible for at least part of the lower CO_2 values observed during this period compared with the values recorded during the previous part of the glaciation (110–70 kyr BP).

In summary, it seems that the atmospheric CO_2 variations recorded in the Vostok core could be explained by two kinds of changes in the oceanic circulation, that is, the deep changes possibly driven by sea level and the surface changes driven by atmospheric circulation. In this case only deep circulation changes could be the cause of the CO_2 variations between the last interglacial and the first part of the glaciation (110–70 kyr), whereas both deep and surface circulation could be responsible for the lower CO_2 values found during the second part of the glaciation (70–15 kyr) relative to the first part. During glacial-interglacial transitions, the CO_2 increase could be initiated by surface circulation changes relayed by the deep circulation changes associated with the sea-level increase.

Conclusions

An atmospheric CO_2 record over the past 160 kyr has been obtained from the Vostok ice core. This CO_2 record is probably the purest available, covering the last climatic cycle. The CO_2 changes thus revealed, which are of global significance, are well correlated with the Antarctic temperature record derived from the ice isotopic profile measured on the same core. Such a high correlation would be expected if CO_2 plays an important role in forcing the climate.

The results also suggest a different behaviour of the relative timing between CO_2 and Antarctic climate changes depending on whether we proceed from a glacial to an interglacial period or vice versa. This may have implications concerning the relation between cause and effect inside the CO_2-climate system, but more detailed measurements in the transition parts of the record are required before firm conclusions can be drawn. Long-term CO_2 changes are dominated by marked glacial-interglacial oscillations between ~190–200 and 260–280 p.p.m.v. A period of ~20 kyr similar to the orbital precession period, appears in the decreasing CO_2 trend covering most of the last glaciation and is supported by spectral analysis. These CO_2 changes could be linked with oceanic circulation changes but a more precise interpretation would in particular require the determination of the $\delta^{13}C$ of the CO_2 extracted from the air bubbles trapped in the ice and a comparable chronology for marine and ice core records.

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Vostok ice core: climatic response to CO_2 and orbital forcing changes over the last climatic cycle

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Vostok climate and CO_2 records suggest that CO_2 changes have had an important climatic role during the late Pleistocene in amplifying the relatively weak orbital forcing. The existence of the 100-kyr cycle and the synchronism between Northern and Southern Hemisphere climates may have their origin in the large glacial-interglacial CO_2 changes.

FROM the Vostok Antarctic ice core drilled by the Soviet Antarctic Expeditions, we have, in two companion articles[1,2], derived time series of the central East Antarctic atmosphere temperature and of atmospheric CO_2 content spanning the past 160 kyr. These studies suggest that over this period the climate at Vostok was, at least in part, driven both by the variations in atmospheric CO_2 and by orbital forcing which would be exerted through insolation changes in the Northern Hemisphere and locally[3]. Here we examine the relative influence of these various forcings on a quantitative basis by calculating the temperature signal as a response to CO_2 and forcings in the Northern Hemisphere and locally. Our simple model can explain >90% of the climate variance at Vostok. It suggests that CO_2 plays an important role in influencing the Earth's climate during the late Pleistocene.

For two decades the Milankovitch hypothesis[4] that the great Northern Hemisphere ice sheets are controlled by the seasonal contrast of insolation at ~65° N has received support, particularly from a thorough analysis of the $\delta^{18}O$ deep-sea record[5,6]. But the implied large amplification of this relatively weak forcing (the total insolation received by the planet varied by <0.6% over the past 10^6 yr), the observed dominant 100-kyr cycle and the synchronism between the termination of major glaciations in the Northern and Southern Hemispheres do not fit this hypothesis well[7-12]. Further developments of the theory of Pleistocene climates have included the nonlinear response of ice sheets to this orbital forcing[8,13-17] and the role of oceanic circulation[11,18,19], ice-shelf destruction[20,21] and sea-level changes[9,21]. More recently the glacial-interglacial CO_2 changes shown from measurements in air trapped in ancient ice[22,23] and later indirectly derived from $\delta^{13}C$ deep-sea core data[24,25], have focused attention on the possible contribution of the CO_2 greenhouse effect to these major climatic changes[10-12,17,25-28].

To address the problem of glacial-interglacial climatic changes, the Vostok ice-core results are important because they give access in the same core to: (1) a continuous isotope temperature series which is, at least qualitatively, of relatively large geographical significance[1] and (2) a direct estimate of the atmospheric CO_2 content which is global in character[2]. These two series are dominated by a clear ~100 kyr signal. They show concentration of variance near orbital frequencies and suggest that there is an interaction between CO_2, orbital forcing and climate on the timescale of glacial-interglacial episodes. Because all the parts of the climatic system (atmosphere, ocean, cryosphere, biosphere) are involved, such interactions are complex. Considering this complexity, then, we shall limit our present purpose to giving and discussing the results of a multivariate analysis between a single climatic output (the Vostok isotope temperature record, ΔT_s, shown in Fig. 1*a*) and multiple climatic inputs. In essence we perform a statistical analysis without specifically accounting for the physical mechanisms involved. We consider three types of climatic forcings: (1) a Southern Hemisphere input, (2) a Northern Hemisphere input, and (3) a CO_2 input.

Methods

These climatic forcings were chosen to cover as far as possible the full range of hypotheses currently proposed in this field. Figure 1 shows corresponding time series, the insolation curves being calculated using the Berger algorithms[29].

As a Southern Hemisphere (SH) input we used either the local insolation (78 °S) received during the entire year (s_1) or the mean daily November insolation at 60 °S (s_2). As mentioned in ref. 3, s_1 shows visual similarities to the Vostok isotope record, which suggests there is a link between ΔT_s and this annual insolation; s_2 is thought to play in important role in the sea-ice extent around Antarctica[30]. In all of the cases considered, the