PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

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Phil. Trans. R. Soc. Lond. B 1992 **338**, 227-234
doi: 10.1098/rstb.1992.0142

The ice core record: past archive of the climate and signpost to the future

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SUMMARY

Ice cores from Antarctica provide multi proxy records of climate and environmental parameters. They have recorded glacial–interglacial temperature changes with cold stages associated with lower snow accumulation and high concentration of aerosols from marine and continental sources. The 160000-year-long Vostok isotope temperature record exhibits signatures of the insolation orbital forcing as well as a close association between climate and greenhouse gas concentrations. These gases are likely to have played an important role in amplifying the amplitude of past global temperature changes. Data from the ice show evidence of anthropogenic impact on atmospheric greenhouse gases (CO_2 and CH_4) over the past 200 years. They suggest a climate sensitivity to greenhouse forcing which is consistent with General Circulation Models simulations for a future doubled atmospheric CO_2. Further ice coring in Antarctica should help to improve our understanding of the climate system.

1. INTRODUCTION

The recovery of environmental history is one of the keys to a better understanding of climatic changes. Palaeo-data help in particular to disentangle human-induced changes from natural behaviour of the system and to put them in perspective, to understand mechanisms, to gain insights on climate sensitivity and to evaluate models to be used in prediction.

In this respect archives of polar ice-sheets provide a wide range of information as they record atmospheric climatic conditions and aerosol and gas composition in consecutive layers over timescales extending so far to 160 ka before present (BP). Results obtained from ice cores in the past few years on the impact of man's activities on greenhouse gases concentration and on the close association between climate and greenhouse gases during glacial–interglacial changes have been largely responsible for the public awareness of the coupled nature of the Earth system (Oeschger 1992). This paper will concentrate on Antarctic data relevant to changes in climate and atmospheric composition of global significance.

2. ICE ARCHIVES

Although we cannot expect to find an ideal recorder in nature, cold polar ice is proving to be a rather remarkably close approximation (Oeschger & Langway 1989; Lorius 1991). Disadvantages are related to the fact that drilling sites are limited geographically and that, because of logistics and technical difficulties, there are so far only a very few cores reaching back to the last ice age. Specific merits are linked with the possibility to obtain high resolution records and largely quantifiable information on the most important climatic parameters: temperature, precipitation rates, atmospheric composition and aerosols loading.

The isotopic fractionation of H and O during evaporation and condensation of water leads to a broadly linear relationship between temperature and the depletion of heavy isotopes in snow precipitation (Dansgaard 1964; Lorius & Merlivat 1977). Thus ^{18}O and D concentration measurements on ice cores allow local surface temperature reconstruction. The content of chemicals in the air at a given site is reflected in impurities contained in snow deposits, although a better knowledge of precipitation mechanisms is needed to establish a precise quantitative link between aerosols and ice impurities (Davidson 1989). Natural ice contains air bubbles that were entrapped during the transformation of snow to ice. Because gases are well-mixed in the atmosphere, measured concentrations can be taken as global value.

For the upper part of the ice sheets the accuracy of the chronology can be very high when annual layers can be counted from seasonal variations of various parameters. Reference horizons can also be used when causal events are documented (e.g. radioactive or volcanic fallouts). Some specific large-scale atmospheric events (e.g. gas and cosmogenic radioisotope concentrations, abrupt climatic changes) can be used to correlate spatially distant records. When clear features in an ice core record can be linked to dated events in another record, these dates can be used to help to control the ice chronology which is essentially based at depth on glaciological models.

3. ICE AGES

There are only three Antarctic records, reflecting mainly atmospheric changes which extend back to the last ice age which culminated around 18 ka BP. The Byrd core is 2160 m long and was drilled in West Antarctica almost 25 years ago. Several thousand kilometers from there the Dome C drilling (900 m) was performed 10 years later in East Antarctica while the Vostok coring programme which started almost 20 years ago obtained a series of cores, the longest and most recent one having reached a depth over 2500 m where the ice is older than 200 ka.

The discovery of cosmogenic ^{10}Be peaks around 35 and 60 ka BP (Raisbeck *et al.* 1987) allowed correlation of the Dome C and Vostok records. Revised timescales show that the two isotopic records and the one from Byrd depict similar climatic events over the last 60 ka, indicating that a single deep ice core may be representative of changes at the continental scale (Jouzel *et al.* 1989). A significant feature of the records is that the last deglaciation was not monotonous as the warming was interrupted by a colder episode. This episode may correspond to the Younger Dryas event detected in the Greenland ice sheet (Dansgaard *et al.* 1989), which lasted about 1000 years and was likely initiated in the Northern Hemisphere. The analysis of air bubbles and ice impurities also indicated large changes of CO_2 (Delmas *et al.* 1980) and aerosols loading (Petit *et al.* 1981; Thompson *et al.* 1981) paralleling the deglaciation. These significant findings were extended back in time by the data obtained from the Vostok ice core.

(*a*) *The last climatic cycle*

The smoothed Vostok temperature profile reported in figure 1 was obtained from a 2083 m deuterium profile and covers the last 160 ka (Jouzel *et al.* 1987). This record is dominated by the ~100 ka glacial–interglacial oscillation with an amplitude of about 6°C. The peak of the previous interglacial is significantly warmer than the Holocene and there are three well-marked temperature minima during the glacial period, separated by two double peaked interstadials with temperatures 3 to 4°C warmer than the Last Glacial Maximum. The chronology established from a two-dimensional ice flow model has an estimated accuracy of 10 to 15 ka at the bottom of the core (Lorius *et al.* 1985). Such an ice model takes into account snow accumulation change with time.

To obtain accumulation changes it was assumed that precipitation rate is governed by the amount of available water vapour which is largely controlled by the saturation vapor pressure of water, i.e. by the air mass temperature. In this way the snow accumulation rate has been estimated from the isotope temperature record, leading to the prediction of a 50% reduction during the Last Glacial Maximum compared to modern values. The ^{10}Be profile provided essential support to this approach (Raisbeck *et al.* 1987). Assuming a constant ^{10}Be flux, the measured concentrations are inversely related to the amount of snow precipitation and indicate a factor of two increase between full glacial and interglacial conditions. Indeed there is a good correlation between these two independent estimates of precipitation.

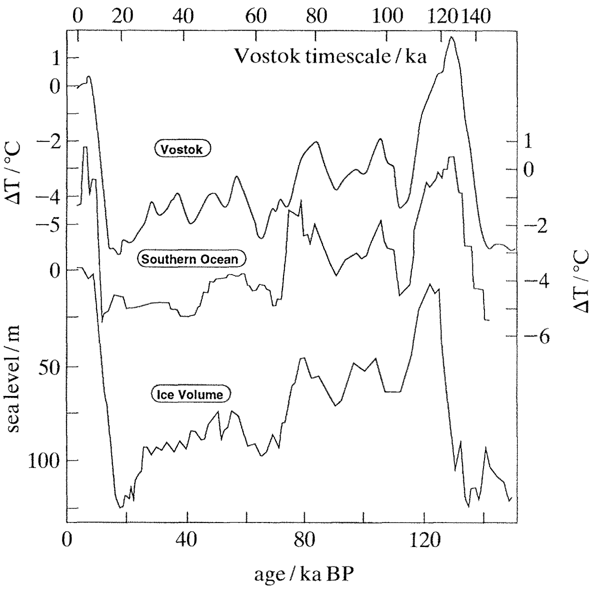

Figure 1. Time series of: the Vostok temperature; the sea surface temperature at the Indian Ocean site MD 84–551 (adapted from Pichon *et al.* (1992)); the δ^{18}O SPECMAP record taken as a proxy of ice volume (lower curve adapted from Martinson *et al.* (1987)) and reported with respect to sea level change.

The lower timescale is the SPECMAP timescale. The Vostok timescale is indicated at the top.

The representativity of the Vostok climate record is of large-scale and to some extent, even global significance. This is illustrated (figure 1) by the high correlation (Jouzel *et al.* 1987) with the marine ^{18}O SPECMAP record (Martinson *et al.* 1987) which essentially characterizes the global ice volume. This is remarkable down to 110 ka BP, as the two records are independently dated. Further back in time there is a discrepancy in the duration and the start of the last interglacial which raises the question of the relative timing of the Vostok and oceanic records. The sea surface temperature reconstructed (figure 1) by Pichon *et al.* (1992) in an Indian ocean site (55°S) is also similar to the Vostok record. Both indicate a glacial–interglacial change of about 6°C which is in the range of that estimated by Broecker & Denton (1989) for high latitude change. This agreement may offer opportunities to propose a common stratigraphic frame for the ice and marine records.

Aside from the ~100 ka oscillation the Vostok temperature record clearly shows a dominant 40 ka signal with minima in good agreement with those of the calculated local insolation which is governed by the obliquity cycle (figure 5). The spectral analysis of the Vostok record also shows a ~20 ka signal. Indeed two precessional peaks near 23 and 19 ka respectively have been identified (Yiou *et al.* 1991). These results fully support the role of astronomical forcing as being the initial causes of the Pleistocene glacial–interglacial cycles.

(*b*) *Climate and aerosols*

Impurities contained in the ice come from different sources: extraterrestrial (e.g. ^{10}Be), continental, marine, volcanic and biospheric.

The aluminium profile (labelled dust in figure 2) is an indicator of continental input. Together with dust (Petit *et al.* 1990), it shows sharp increases during cold stages (De Angelis *et al.* 1987; Legrand *et al.* 1988*a*) which are explained by enhanced source strength (extension of arid areas, greater exposure of continental shelves due to sea level lowering, increased wind speeds over the continents) and lower accumulation rates.

Despite the greater expansion of sea ice, the marine sea-salt (represented by Na in figure 2) concentration was larger during glacials. This likely reflects an increase in wind speed over the source area and, more generally, in the meridional circulation (Petit *et al.* 1981) as well as a lower snow accumulation. Chemical studies of ice cores using proxies such as acidity have also recorded past volcanism. There appears (figure 2) to be no long-term correlation between climate and volcanic acitivity (Legrand *et al.* 1988*a*). Current research concerns the study of biogeochemical cycles through the reconstruction of sulphur, nitrogen and carbon cycles. We will examine specific aspects related to climatic change in a later section.

(*c*) ***Climate and greenhouse gases***

The best documented CO_2 records from ice cores arise from Byrd (figure 3) for the last deglaciation (Staffelbach *et al.* 1991), and from Vostok (figure 4) for the last climatic cycle (Barnola *et al.* 1987, 1991). The main results of greenhouse gases measurement are as follows.

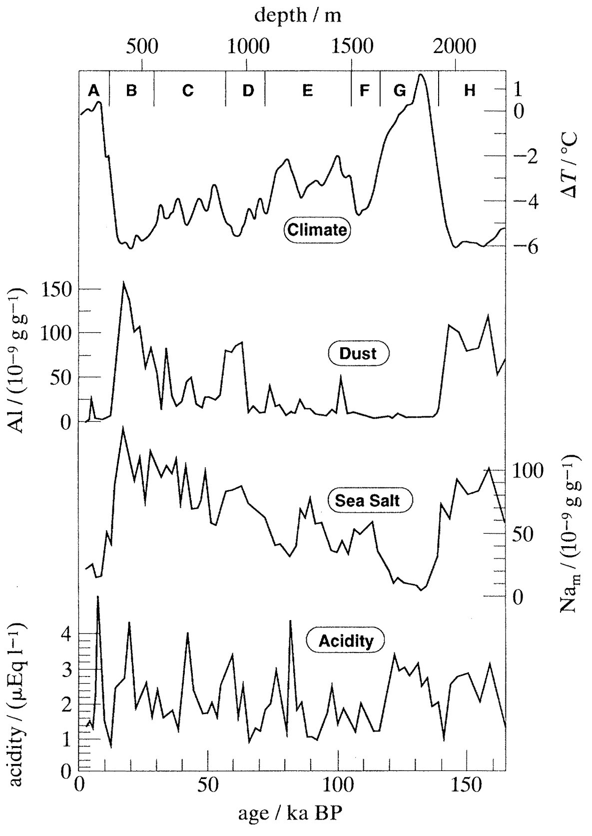

Figure 2. Time series along the Vostok core of: the atmospheric temperature record (adapted from Jouzel *et al.* (1987)); the aluminium content (adapted from De Angelis *et al.* (1987)); the sodium content (labelled sea salt and adapted from Legrand *et al.* (1988*a*)); the acidity (adapted from Legrand *et al.* (1988*a*)).

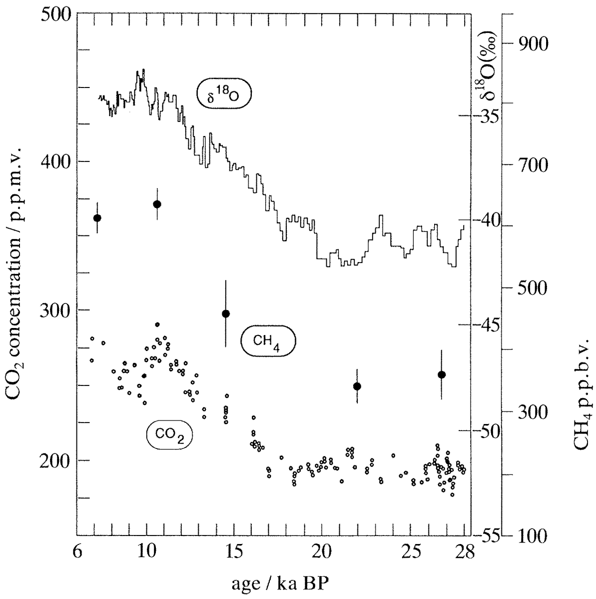

Figure 3. Byrd ice core: changes of CO_2, CH_4 and $\delta^{18}O$ of ice (used as a proxy for temperature) during the last deglaciation (from Staffelbach *et al.* 1991; Stauffer *et al.* 1988). Age scale: C. Hammer, personal communication.

1. Last Glacial Maximum concentrations were lower than during the pre-industrial Holocene by 25–30% for CO_2 (Delmas *et al.* 1980) and by 40–50% for CH_4 (Stauffer *et al.* 1988; Raynaud *et al.* 1988).
2. Rapid changes have been measured for CH_4 during the last deglaciation (Chappellaz *et al.* 1990). Rapid changes have also been detected for CO_2 in Greenland ice between 30 and 40 ka BP (Stauffer *et al.* 1984) in parallel with rapid shifts in temperature (oxygen isotope ratio); a finding which has not been confirmed in Antarctic cores.
3. There is a remarkable correlation between both CO_2 and CH_4 and climate over the last glacial–interglacial cycle (Barnola *et al.* 1987; Chappellaz *et al.* 1990).

These observed changes emphasize the biosphere–climate link and imply modifications of sources and sinks involving different processes. CO_2 changes are likely governed by oceanic circulation and marine productivity (Broecker & Peng 1989) while CH_4 may reflect extent and emission fluxes from continental wetlands (Chappellaz *et al.* 1990) and eventually changes in permafrost covered areas. The mechanisms involved are not fully understood, especially for CO_2, but one should note that orbital frequencies are present in the greenhouse gas profiles from Vostok. This finding further supports the hypothesis that orbital changes are the initial cause of ice ages.

(*d*) ***Palaeoclimate and forcing factors***

Over the past two decades the Milankovitch astro-

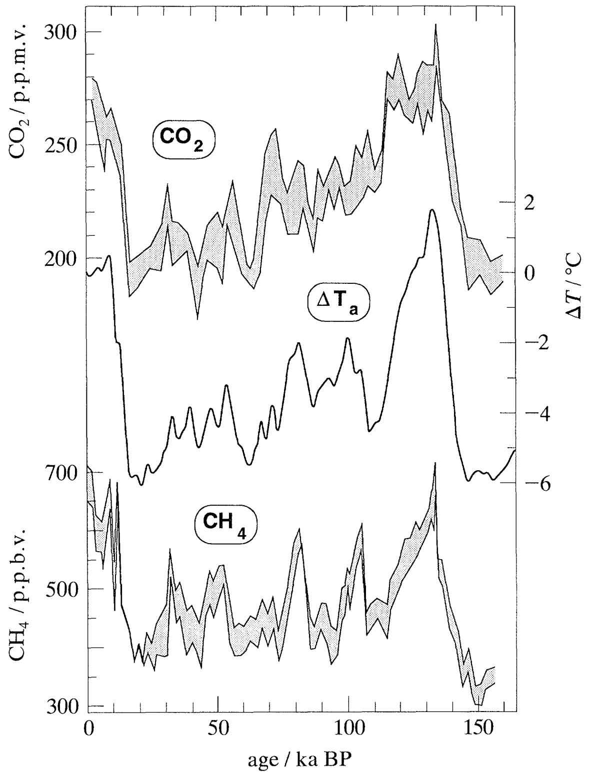

Figure 4. Vostok ice core. Variation over the last climatic cycle of: the CO_2 atmospheric concentration (adapted from Barnola *et al.* (1987)); the atmospheric temperature change over Antarctica (adapted from Jouzel *et al.* (1987)); the CH_4 atmospheric concentration (adapted from Chappellaz *et al.* (1990)).

Note the oscillation during the last deglaciation, possibly corresponding to the Younger Dryas northern hemisphere event. For CO_2 and CH_4 the envelope shown has been plotted taking into account the different uncertainty sources whereas the temperature record corresponds to a smoothed curve.

nomical theory of palaeoclimates has received considerable support, in particular from the ^{18}O marine records (Berger 1988). This theory claims that the changes in the Earth's orbital and rotational parameters have induced significant changes in the seasonal and latitudinal distribution of insolation to force glacial-interglacial climate shifts through the waxing and waning of ice sheets in the northern hemisphere. However, the existence of a strong 100 ka cycle and the synchroneity and similar amplitude of temperature changes in both polar regions cannot be easily explained by this theory. The discovery of the link between climate and the composition of the atmosphere has led to the idea that CO_2 (Shackleton & Pisias 1985; Saltzman 1987; Barnola *et al.* 1987) and CH_4 (Chappellaz *et al.* 1990) changes have also played a significant role in glacial–interglacial climatic changes.

Genthon *et al.* (1987) and Lorius *et al.* (1990) took advantage of the simultaneous Vostok records of forcings and climate, which reflect equilibrium conditions, to investigate the possible role of greenhouse gases in long term temperature changes. They performed a multivariate analysis which shows that 90% of the variance of the temperature record can be explained by four climate inputs (figure 5). The aerosol loading and non sea-salt sulfates (Legrand *et al.* 1988*b*) which may affect the albedo of clouds, and the local insolation change have been found to play a minor role. Only both the northern hemisphere orbital forcing represented by the $\delta^{18}O$ marine record, a proxy of the continental ice volume, and the radiative greenhouse forcing linked with CO_2 and CH_4 concentration changes appear to have had a similar and major contribution of the order of $50 \pm 10\%$. This means that about 3 of the 6°C depicting the last glacial–interglacial change at Vostok would be associated with a greenhouse radiative forcing of $\sim 2\ \mathrm{W m^{-2}}$ corresponding to an equilibrium temperature change of ~0.7°C, i.e. with no climatic feedback.

Such feedbacks act within the climate system to amplify and modify the original external forcing. Typical fast feedbacks which can be associated with CO_2 and CH_4 forcing are the changes in atmospheric water vapour and in sea-ice cover after a change in temperature, affecting the greenhouse effect and the marine albedo respectively. Slow feedbacks are, in

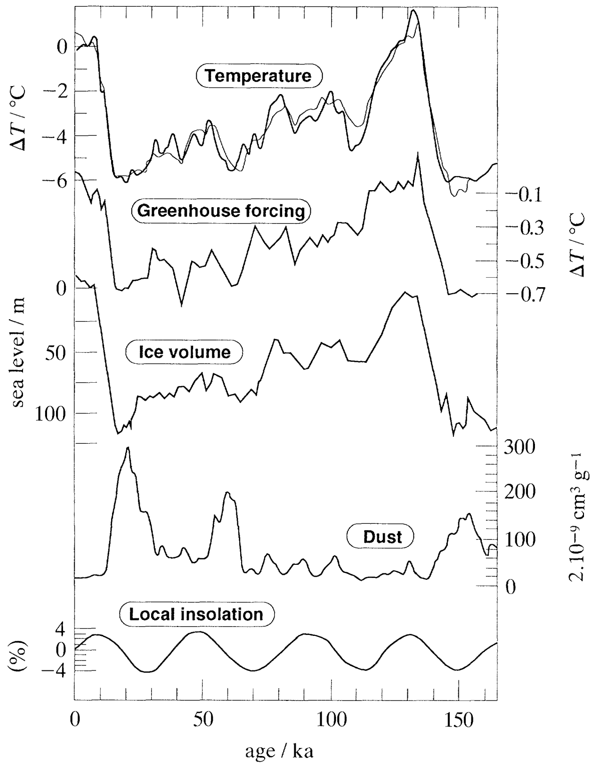

Figure 5. Time series of the Vostok climatic record and of climatic forcings used in the multivariate analysis: atmospheric temperature record over Antarctica (heavy curve) and reconstructed temperature record (light curve); direct greenhouse radiative forcing accounting for CO_2 and CH_4 variations; ^{18}O SPECMAP record taken as a proxy of ice volume change (adapted from Martinson *et al.* (1987) with a sea level scale); the dust Vostok record (adapted from Petit *et al.* (1990)); percentage change in total insolation at the Vostok latitude (78°S) during the entire year.

Vostok derived curves (temperature, greenhouse forcing and dust) have been redated for the period before 110 ka BP in such a way to put in phase the Vostok temperature and the marine record.

particular, the change in terrestrial albedo and other parameters related to the waxing and waning of large ice sheets.

Although the multivariate analysis of the Vostok data is a rather simplistic approach (assuming in particular independent inputs and linear effects on climate) the results are in agreement with simulations of the ice-age climate over Antarctica using General Circulation Models performed by Broccoli & Manabe (1987). Due to polar amplification of climatic changes (Ramanathan 1988), a glacial–interglacial change of 6°C inferred from the Vostok data is well consistent with a globally averaged value of ~4–5°C. This and the similarities observed between the Vostok temperature profile and other palaeorecords of global character suggest in fact that CO_2 and CH_4 changes (including feedback mechanisms) may explain about 50% of the glacial–interglacial change at a global scale. Indeed Broccoli & Manabe (1987) found that greenhouse gas increase and associated fast feedbacks could account for ~40% of the glacial–interglacial averaged warming. Rind *et al.* (1989) also indicated that an average warming of 2.5°C would result from a CO_2 increase similar to the one obtained from ice cores, corresponding to at least 50% of the glacial–interglacial warming given by various simulations (Hansen *et al.* 1984). Although consensus is not a perfect guide in science, the general consistency of the results obtained by independent approaches supports the belief that the direct greenhouse forcing and associated fast feedbacks could explain a global warming of over 2°C corresponding to an equilibrium radiative temperature change of 0.7°C.

It is worth noting that such conclusions do not require a solution to the 'chicken and egg' problem, i.e. to fully understand the causes of greenhouse gas changes and the sequence of the forcing factors. However in a recent review Raynaud & Siegenthaler (1992) point out several facts which further support the role of CO_2 and CH_4 changes in glacial–interglacial climatic changes. Although there are dating uncertainties, they compared marine and ice records using in particular the $\delta^{18}O$ of atmospheric oxygen as obtained from ice cores, a proxy for changes in the marine $\delta^{18}O$ and hence in the continental ice volume (Sowers *et al.* 1991).

They concluded that during deglaciations both CO_2 and CH_4 increased approximately in phase with temperature in high southern latitudes but preceded any significant melting of continental ice (figure 6). The radiative forcing due to greenhouse gases therefore was ahead of the climate forcing due to the retreating ice sheets. Also, during the deglaciation, a CH_4 oscillation detected in the Vostok core (figure 4) is most likely linked to the Younger Dryas event. Lead and lag approaches show however the complexity of the climate system. During the initiation of the glaciation, CH_4 decreased also in phase with southern ocean temperature, but CO_2 lagged by several ka behind (figure 7).

4. MAN'S IMPACT ON THE ATMOSPHERE

Precise and continuous measurements of the atmospheric CO_2 and CH_4 contents started only two or three decades ago, drawing attention to the impact of human activities on the observed increases. The analysis of air bubbles trapped in Antarctic ice recently allowed an accurate reconstruction in particular of CO_2, CH_4 and N_2O changes over the last few centuries (figure 8). The results indicate a pre-industrial atmospheric concentration of about 280 p.p.m.v. for CO_2 (Neftel *et al.* 1985; Raynaud & Barnola 1985; Pearman *et al.* 1986). The increase to present (more than 350 p.p.m.v.) can be unambi-

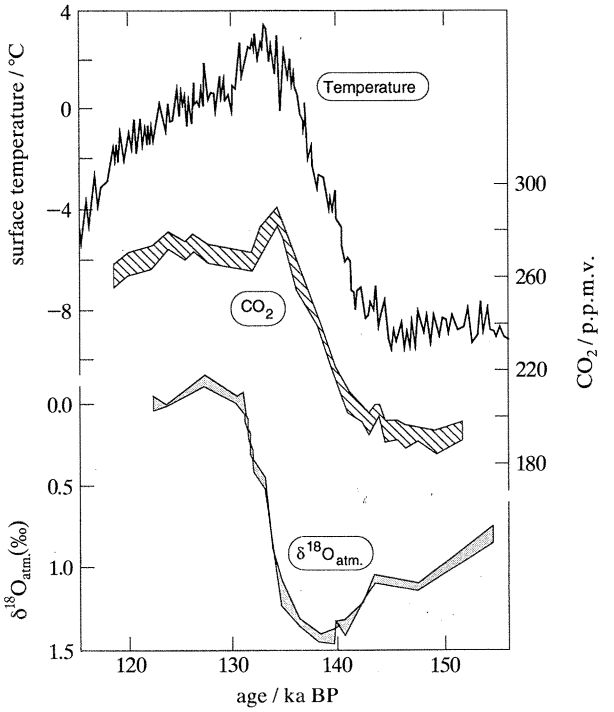

Figure 6. Vostok ice core: changes of temperature, CO_2 and $\delta^{18}0$ of atmospheric oxygen during the penultimate deglaciation (from Sowers *et al.* 1991).

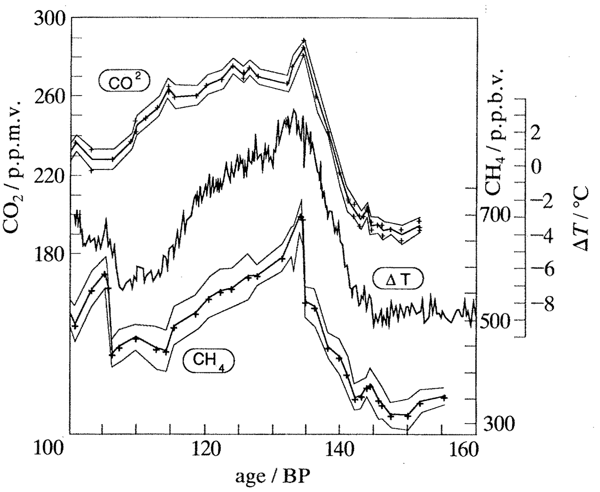

Figure 7. Vostok ice core: changes of CO_2 (top), CH_4 (bottom) and temperature (middle curve), during the 100–160 ka BP period including the penultimate deglaciation the interglacial and the inception of the following glaciation (from Chappellaz 1990; Barnola *et al.* 1991).

guously attributed to human activities, primarily fossil fuel burning and, to a lower extent, deforestation (Oeschger & Siegenthaler 1988). An astonishing fact because human contribution is minor compared to the much larger natural CO_2 exchange fluxes.

As for CH_4, ice core data (Stauffer *et al.* 1985; Pearman *et al.* 1986) show that the increasing trend started around 200 years ago, with the result that the concentration up to now has increased by a factor of about 2.5. Part of the observed increase could be due to a reduction in the oxidation capacity of the atmosphere, but the largest fraction is attributed to rice cultivation, animal husbandry, fossil fuel recovery and burning, and landfills. These human sources account for about half of present CH_4 emissions.

Two striking features of these results can be pointed out: (i) CO_2 and CH_4 concentrations are now much larger than at any time in the past 160 000 years; and (ii) CO_2 and CH_4 trends parallel the growth of the world population (figure 8).

The anthropogenic greenhouse gas increases are now causing a radiative forcing larger than 2 Wm^{-2}; this forcing, corresponding to a doubling of equivalent CO_2 concentration, will likely reach a level of 4–5 Wm^{-2} by the middle of the next century assuming no control of human emissions (IPCC 1990).

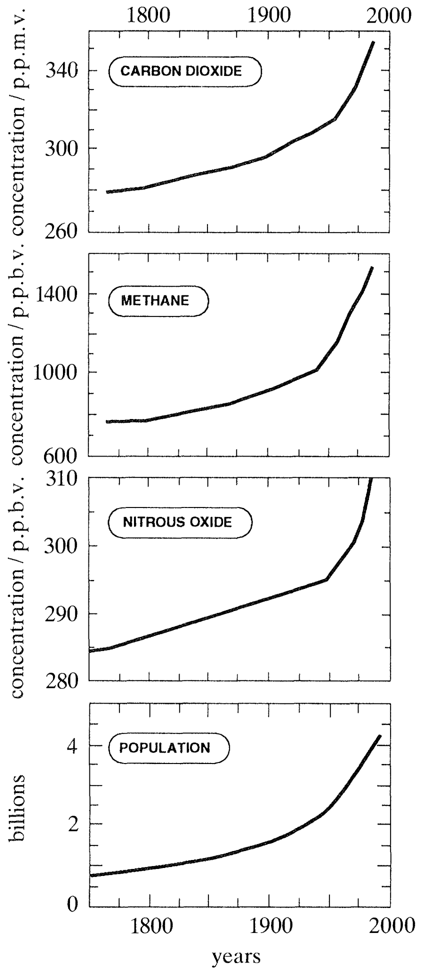

Figure 8. Increase of greenhouse gas concentrations over the last 200 years from antarctic ice cores. CO_2 (from Oeschger & Siegenthaler 1988), CH_4 (from Pearman *et al.* 1986), N_20 (from Khalil & Rasmussen 1988). The population growth is included for comparison.

5. CLIMATE AND GREENHOUSE FORCING

It is likely that other natural or man-made (e.g. changing atmospheric aerosols; Charlson *et al.* 1987) or internal mechanisms will influence climate in the near future. But it is also likely that the greenhouse intensification effect will play a major role in shaping the climate of the coming century.

One of the main problems in estimating the possible climatic impact of a doubled greenhouse radiative forcing from General Circulation Models, is to evaluate the sensitivity of the earth's climate to this forcing which corresponds to a direct radiative effect of 1.2°C. The evidence from the modelling studies and also from observations and sensitivity analysis indicates (IPCC 1990) that the equilibrium temperature increase will likely lie within the range 1.5 to 4.5°C. This would correspond to a climate sensitivity of 1.3 to almost 4, the amplification being due to fast feedback processes linked with water vapour, sea-ice and clouds, the later being the cause of the main uncertainty.

Palaeoclimate modelling and ice core analyses indicate that the increase of CO_2 and CH_4 caused a direct radiative forcing of 0.7°C and a warming of 2°C including feedback mechanisms at the glacial–interglacial change. The ice core results over a full glacial–interglacial cycle then suggest that a doubled CO_2 induced averaged temperature warming of 3 to 4°C may be a realistic figure.

Despite the relative agreement between scarse ice core data and modelling approach, there is still much progress to be made in understanding past climate to help narrow uncertainties in predicting future changes. We need a much better understanding of the physical, chemical and biological processes by which subtle changes in insolation are amplified to induce glacial–interglacial changes. Knowing the sequence of events and the exact timing of forcings and of their climatic responses in various parts of the Earth system, is essential; in this respect obtaining and comparing data from both northern and southern hemispheres ice sheets are particularly important. A strong interaction between data acquisition and modelling of past changes including the atmosphere, ocean cryosphere, hydrosphere and land and biogeochemical cycles has also to be developed. As for Antarctica, coupling regional to global models is a major task, while organizing an ice core drilling network at specific sites to answer remaining key questions on short-term and long-term changes should have a high, if not the first, priority.

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Discussion

G. Weller (*Geophysical Institute, University of Alaska, U.S.A.*). The ice core record shows that the temperature decrease at the beginning of ice ages is very gradual, but on the other hand ice ages end very abruptly with large, short-term temperature increases. What is the reason for this?

C. Lorius. The explanation may lie in the time required to build large ice sheets in the Northern Hemisphere while desintegration may arise much more rapidly.

I. N. McCave (*Department of Earth Sciences, University of Cambridge, U.K.*). What is the precision (uncertainty) of estimation of time for records of temperature from ice (deduced from isotopic studies) and gas composition from bubbles? Is there any way yet in any existing cores of determining whether change in gas composition leads or lags change in temperature?

C. Lorius. The time uncertainty between the isotopic temperature record and atmospheric composition is mainly due to the delay of close-off of air bubbles. This delay varies with the site characteristics and may be as large as several thousands of years for low accumulation areas in Antarctica. Leads and lags can be nevertheless estimated by taking into account this correction. During deglaciation temperature and concentration of greenhouse gases are about in phase while the temperature seems to be in phase with CH_4 but leads CO_2 when entering into the glaciation.

C. Moore (*British Antarctic Survey, Cambridge, U.K.*). A 'Younger Dryas' type of climate rebound has been observed at the end of the last few glacial periods in high resolution ocean sediment cores. The Vostok CO_2 and CH_4 records seem to show the Younger Dryas at the end of the last glaciation. Do they show a similar feature at the end of the previous glaciation?

C. Lorius. The Vostok CH_4 record does indicate concentration changes which could be associated with the Younger Dryas event. CO_2 results indicate a plateau rather than an oscillation. No such features have been observed in the previous deglaciation.