Ice-core records of global climate and environment changes

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Precipitation accumulating on the Greenland and Antarctic ice sheets records several key parameters (temperature, accumulation, composition of atmospheric gases and aerosols) of primary interest for documenting the past global environment over recent climatic cycles and the chemistry of the pre-industrial atmosphere. Several deep ice cores from Antarctica and Greenland have been studied over the last fifteen years. In both hemispheres, temperature records (based on stable isotope measurements in water) show the succession of glacial and interglacial periods. However, detailed features of the climatic stages are not identical in Antarctica and in Greenland. A tight link between global climate and greenhouse gas concentrations was discovered, CO₂ and CH₄ concentrations being lower in glacial conditions by about 80 and 0.3 ppmv, respectively, with respect to their pre-industrial levels of 280 and 0.65 ppmv. Coldest stages are also characterized by higher sea-salt and crustal aerosol concentrations. In Greenland, contrary to Antarctica, ice-age ice is alkaline. Gas-derived aerosol (in particular, sulfate) concentrations are generally higher for glacial periods, but not similar in both the hemispheres. Marine and continental biomass-related species are significant in Antarctica and Greenland ice, respectively. Finally, the growing impact of anthropogenic activities on the atmospheric composition is well recorded in both polar regions for long-lived compounds (in particular greenhouse gases), but mostly in Greenland for short-lived pollutants.

1. Introduction

Year after year, over millennia and millennia, snow has been accumulating on the Antarctic and Greenland ice sheets. By compaction, deposited snow progressively transforms into firn and ultimately to ice (figure 1). During this process, an array of various atmospheric parameters are recorded, forming a unique archive of great value for climatic and environmental studies (e.g. Delmas 1992). Information preserved in polar ice caps can be retrieved by ice core drilling and analysis. Vostok, GRIP (GReenland Ice core Project) and GISP2 (Greenland Ice Sheet Project 2) have been the most famous recent operations carried out by the international community of glaciologists, and a wealth of climate-related data have been obtained from several ice cores drilled during the past two decades at various polar sites (figure 2).

Several measurements are performed on the ice cores. Palaeotemperature reconstruction is based on water isotope fractionation processes taking place in the atmospheric water cycle (Craig 1961; Dansgaard 1964). It has been demonstrated experimentally that the “isotopic temperature” (isotope composition of ice) reflects mainly the mean annual temperature at the precipitation site. Water stable isotopes measured on ice cores are therefore used as proxies for palaeotemperature.

Secondly, past atmospheric gas composition can be obtained by analyzing the air bubbles entrapped in ice during the slow transformation of firn into ice. This process occurs typically between about 50 and 120 meter depth (depending on accumulation rate and temperature, Raynaud et al 1993). For long-lived gases like greenhouse gases, their measured composition in the ice can be taken as their global value.

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various climatic conditions. On the basis of ice core data, it is therefore possible to compare man-induced and climate-induced atmospheric composition changes. We will see that in many cases, the anthropogenic effect exceeds the natural fluctuation range. For instance, the present-day atmospheric levels of two major greenhouse gases (CO₂ and CH₄) are unprecedented over the last 400 ka. This may be the most important information provided, up to now, to Global Change science by polar ice core researchers.

2. Methods

2.1 Isotope measurements

Mass-spectroscopic measurements of thousands of ice samples are necessary to obtain detailed paleotemperature profiles. Water isotope (HDO and (H₂¹⁸O) concentrations (called δD or δ¹⁸O) are expressed in permil units with respect to SMOW reference (SMOW = Standard Mean Ocean Water). For years, the empirical linear relationships linking δD (or δ¹⁸O) of present polar snow to mean annual temperature of the study area have been used to reconstruct paleotemperatures. The theoretical basis of the method was first established by Dansgaard (1964) and later regularly improved by various authors (Lorius and Merlivat 1977; Dansgaard and Oeschger 1989). Deuterium excess

\[ d = \delta D - 8\delta ^{18}O, \]  

according to Dansgaard (1964) is a parameter related to the geographical location where water vapor originated. The validity of using the observed current relationships for paleotemperature reconstruction was supported for years by comparing various other proxy data with ice-core results. During the last three decades, most deep ice-core isotope profiles have been interpreted by climatologists in terms of past temperature records on the basis of simple isotopic models. However, most recently, temperature measurements in the GRIP bore hole (Johnsen et al 1995a) showed that the temperature warming when passing from LGM (Last Glacial Maximum) to modern climate conditions was probably double (i.e. about 20°C) than previously estimated from isotope measurements. GCM (General Circulation Model) analysis is currently being used to obtain a better estimate of glacial/interglacial temperature changes from Greenland and Antarctic ice cores (Krinner et al 1997). In the wake of important palaeoclimatic data obtained from the recent Greenland and Antarctic deep ice cores, Jouzel et al (1997) have assessed the validity of temperature reconstruction from water isotopes in ice cores. Despite disagreements among some data sets, calculation estimates and modelling, the authors conclude that the use of the isotope palaeothermometer appears justified.
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Figure 2. Map of the two major polar ice sheets (Greenland and Antarctica) with indication of the most important drilling sites.
For the measurement of radioactive isotopes produced by atmospheric nuclear tests, low level \( \alpha, \beta, \) or \( \gamma \) counting techniques have to be used. Accelerator Mass Spectrometry (AMS) technology made it possible to obtain detailed \(^{10}\)Be profiles from just a few kg (or even less) ice samples. \(^{10}\)Be data are used for calculating past snow accumulation rates and solar cycle fluctuations (see McHargue and Damon 1991, for a review).

2.2 Electric conductivity measurements (ECM)

It is worth mentioning about the ECM of ice cores. This nondestructive technique, which has to be carried out at low temperatures \((-15^\circ \text{C})\), is a good proxy of the acidity of the ice (Hammer 1980). It is most frequently used in the field for detecting acid spikes of volcanic origin and for discriminating along deep ice cores the glacial (alkaline in Greenland, slightly acidic in the Antarctic) from the acidic interglacial ice layers. It is a direct current (dc) method. More recently, an ac method, called the dielectric profiling technique (DEP), has been developed by Moore and Paren (1987). It responds both to the acid and salt content of the ice (Moore et al 1989).

2.3 Measurements of trace constituents

Polar ice is an extremely pure material and its analysis needs great care and sophisticated analytical techniques. The total amount of gas which can be extracted from polar ice is of the order of 0.1 ml g\(^{-1}\) at STP, less when the ice was formed at high elevation sites, more at low elevation. Concentrations of major soluble ions (e.g. sulfate or nitrate) are frequently in the micro or sub-micro equivalent per liter range. In most cases, the use of clean rooms for sub-sampling operations is essential for obtaining reliable data. Gas entrapped in air bubbles can be recovered either by melting ("wet method") or by crushing ("dry method") the ice. 50 g ice samples (or less) are sufficient for gas chromatography measurements of greenhouse gases. Methods for recovering and analyzing palmo-atmosphere samples for \( \text{CO}_2 \) have been critically reviewed recently by Wilson and Long (1997).

For major ionic species down to the sub-ppb level, ion chromatography is most commonly used. Atomic absorption, and more recently ICP-MS, allows one to measure ppt levels of elements. Microparticle counting is used to determine the insoluble fraction. Continuous flow measurement methods suitable for rapid field determinations of a few soluble species (calcium, ammonium, hydrogen peroxide, formaldehyde) have been developed recently (Fuhrer et al 1993; Sigg et al 1994).

2.4 Establishing the ion balance of soluble impurities

The ice samples have generally to be melted before being analysed. Therefore the initial chemical compounds from which the ions originate are difficult to establish. In practice some assumptions can be made and it is possible to learn about their sources provided that all ionic species have been determined. When a great number of samples is measured, the interpretations become more certain.

The ion balance (i.e. \( \Sigma \) cations = \( \Sigma \) anions, concentrations expressed in \( \mu \text{eq} \text{. l}^{-1} \)) of pre-industrial polar precipitation can be written, if we consider only major ions:

\[
[H^+] + [Na^+] + [Mg^{++}] + [Ca^{++}] + [NH_4^+] = [SO_4^{--}] + [NO_3-] + [Cl^-] + [HCO_3^-].
\]

This equation is useful to interpret the chemical composition of Holocene Antarctic ice. Additional ions may have to be introduced in equation (1), in particular for Greenland snow: in present pre-industrial climatic conditions, light carboxylic acids may contribute to ice acidity whereas, for glacial ages, carbonates contributed by crustal dust are overwhelming in the ion balance of the ice, which is, in this case, alkaline.

In any case, for present times, the results obtained from Antarctica and Greenland ice sheets demonstrate clearly that the chemistry of snow is not fundamentally different in both polar regions: gas-derived acids are dominant, \( \text{H}_2\text{SO}_4 \) in Antarctica, \( \text{HNO}_3 \) in Greenland.

2.5 Dating

The age of the ice is a key parameter in palaeoclimatic studies. Generally, the accuracy of the dating decreases with depth. Three methods, frequently in combination, are commonly used to date the snow and ice layers (Hammer 1989).

2.5.1 Seasonal variations

The concentrations of most species (except gases) in snow exhibit marked seasonal variations which can be used for dating purposes. It is the case of water stable isotopes, but also of chemical species such as acids, hydrogen peroxide, sea salt, dust etc. However, due to the possible reworking of deposited snow by wind and to the migration processes which may affect soluble species in the firn layers, seasonal variations are sometimes blurred. Moreover, due to thinning of ice layers, they tend to vanish progressively with depth. In this respect, seasonal variations of insoluble dust survive the longest. In any case, seasonal variations are difficult to observe at sites with low accumulation rates (<5 g cm\(^{-2}\) a\(^{-1}\)) and the method therefore fails in central Antarctic areas.

2.5.2 Reference horizons

Special levels linked to large volcanic eruptions (Hammer 1980), atmospheric nuclear tests or even natural phenomena (e.g. \(^{10}\)Be peaks), are frequently used as time markers (Stauffer 1989). The limit and
the precision of the method are dictated by the knowledge of the ‘age’ of the event horizons. This method is particularly useful to compare the time scale of deep ice cores.

2.5.3 Ice modelling

Deep ice cores are generally dated using steady state models of the ice sheets which provide an approximate depth-age relationship (Reeh 1989). Over the Holocene (i.e. the last 10,000 years), the accuracy of the method is satisfactory, but glaciologists are less confident in the dating of ice-age ice, in particular owing to the uncertainty in past snow accumulation rates (the key parameter for central polar area models). For instance, the two-dimensional ice flow model used for the Vostok ice core provided a time scale with an uncertainty of 20 ka at 220 ka BP (Jouzel et al 1993).

When the accumulation is high as in Greenland, dating is easier. A comparison of several dating methods (visual stratigraphy, oxygen isotope variations, ECM, volcanic signals, laser-light scattering from dust and major ion chemistry) is given by Meese et al (1997) for establishing the depth-age scale of the recent GISP 2 ice core. The ice at 2800 m is dated at 110 ka B.P., with an estimated error ranging from 1 to 10% in the top 2500 m and averaging 20% below.

Note that the age of the air contained in the bubbles is markedly younger than the age of the ice in which it is enclosed, since bubble close-off occurs in depth, well after snow deposition, as earlier mentioned. Dating of air entrapped in polar ice is therefore a complex issue (e.g. Raynaud et al 1993).

3. Natural changes

3.1 Vostok studies

The study of polar ice has given a new insight into the past history of global climate changes over the past few hundred thousand years. In particular, measurements on the Vostok ice core has lead to important advances in understanding past climate and environmental changes over glacial-interglacial cycles. In this respect, the initial temperature profile of Vostok Station, spanning a full glacial-interglacial cycle and later improved and extended, can be used as a pattern (Lorius et al 1985).

Drillings were initiated in 1970 by the Arctic and Antarctic Research Institute of Leningrad, USSR at this East Antarctic site (78° 28’ S, 106° 48’ E, elevation: 3490 m, mean annual temperature: −55°C). In the ensuing three decades, the drilling has considerably progressed and the operation has become international (Russian-American-French cooperation). It is estimated that presently about 300 m of ice are still to be drilled, but the lake detected under the ice sheet at this location prevents the completion of the drilling to the bed rock. From 160 ka studied and published in 1987 (Jouzel et al 1987; Genthon et al 1987), the records were first extended in 1993 back to 220 ka (Jouzel et al 1993; Jouzel et al 1996), which represents two full ice ages and even the end of the preceding interglacial. The analyses already carried out on the recent cores indicate that the Vostok ice record is now covering four full glacial and interglacial climatic stages, i.e. about 426 ka (Petit et al 1997). The chronology correlates satisfactorily with oceanic records.

The 1987 Vostok record offered for the first time the opportunity to demonstrate the link between continental temperature and the orbital geometry of the Earth: the role of astronomical forcing as being the initial cause of the pleistocene glacial-interglacial cycles (“Milankovitch theory”, Berger 1988) was fully confirmed. In particular, spectral analysis demonstrates that the Vostok isotope record is dominated, aside from the 100 ka eccentricity cycle, by a strong signal of about 40 ka, corresponding to precession of the equinoxes. The axial tilt cycle (slightly above 20 ka) was also observed.

Data show that interglacial periods have a relatively short duration in comparison to glacial ages. During the latter, temperature fluctuates significantly in accordance with the various cycles mentioned earlier. The penultimate glacial period (PGP), lasting from about 140 to 200 ka B.P., appears to have been more uniformly cold than the last glacial maximum (LGM). The strong correlation between both CO₂ and CH₄ concentrations and climate over the last
gracial-interglacial cycle (Barnola et al 1987; Chappellaz et al 1990) is remarkable. CO₂ and CH₄ concentrations were found to be low (190–200 and 0.35 ppmv, respectively) in cold stages and high (260–280 and 0.65 ppmv, respectively) in the warm stages. These figures have been roughly confirmed from the recently extended Vostok records (Barnola et al 1991; Raynaud et al 1993; Jouzel et al 1996): CO₂ concentrations are low from 140 to 190 ka B.P., with values similar to those observed for the second part of LGM. Also similar, or even sometimes slightly lower than during the LGM, the lowest methane concentrations are observed only for the last stage of PGP. A linear correlation links pre-industrial CO₂ and CH₄ concentrations over the entire study period (figure 3).

A major feature of the ice-age ice at Vostok is its high content of continental dust and sea-salt aerosol as shown by the concentration patterns of insoluble dust particles (Petit et al 1990), sodium and calcium (Legrand et al 1988). This effect had already been reported a decade earlier at other polar sites (Cragin et al 1977). The changes measured in ice depend on several factors (emission rates, meridional transport, atmospheric transformation, deposition mechanism) which all may have changed in the past in relation with climate. GCM simulations are now frequently used to interpret the experimental data (Genthon and Armengaud 1995).

In the Southern Hemisphere, the atmospheric circulation has not been so dramatically modified as in the Northern Hemisphere (see below). Most recent investigation (Basile et al 1997) shows that over the last glacial and interglacial periods, the dominant source of dust for East Antarctica was always the southern part of South America, as suggested previously by Delmas and Petit (1994). The geographical extent of this source was strongly modulated by sea-level changes. Despite the high inputs of crustal dust in glacial conditions, Vostok ice remained acidic all along the study time periods (Legrand et al 1988).

Concentrations of ions related to the major global S and N cycles have been determined. Nitrate deposition in Vostok snow increased during glacial periods in relation with crustal dust inputs (Legrand et al 1988). Regarding the sulfur cycle, the authors concluded from ice core data that marine biogenic DMS (dimethylsulphide) emissions around Antarctica were enhanced during cold climatic stages (Legrand et al 1991, 1992a), a suggestion which needs further confirmation. The two marked peaks of ¹⁰Be concentrations around 35 and 60 ka B.P. were interpreted as reflecting changes in global production of cosmogenic radio-isotopes (Raisbeck et al 1987).

3.2 GRIP and GISP information

GRIP (Greenland Ice core Project, European; Stauffer 1993) and GISP2 (Greenland Ice Sheet Project, American) started both in 1989 at Summit, central Greenland. The drilling reached the bedrock in summer 1992 and 1993, respectively.

The isotope measurements from both the ice cores confirmed that the climate of the Northern Hemisphere was frequently unstable (Dansgaard et al 1993; GRIP Project Members 1993). Rapid variations are observed for glacial ages and climatic transitions (Johnsen et al 1992). For instance, 22 interstadials were found over the last glacial period (Dansgaard et al 1993). More surprisingly, drastic climate variations were also observed for part of the last interglacial (called “Eemian” 140–110 ka B.P., a relatively warm period, often suggested as an analog to our present climate after a greenhouse warming). However, this climatic interpretation of the variations observed in GRIP for interglacial climatic conditions became questionable following the publication of the results obtained in GISP2. Both data sets are in excellent agreement up to 2700–2750 m depth, but for the bottom 10% of the core isotope records differ markedly (Taylor et al 1993; Grootes et al 1993; Jouzel et al 1994) (figure 4). It is probable that these differences result from flow deformation occurring in ice layers located in the last hundred meters, close to the bedrock (Johnsen et al 1995b).

GRIP and Vostok time scales correlate very satisfactorily over the last ~ 100,000 years. The agreement is less convincing for the older climatic periods due to the glaciological disturbances mentioned earlier. Inspite of all the difficulties encountered on the deepest part of these two recent Greenland cores, these analyses have provided a wealth of high quality paleoenvironmental information gathered from the upper hundreds of meters. In addition to climatic phenomena, GRIP and GISP results revealed the relative importance of continental biological processes for atmospheric composition in comparison with Antarctica where the influence of marine biogenic activity is dominant. Measurements show that emissions from boreal forest fires and vegetation play a major role in atmospheric chemistry (Legrand et al 1992b, 1995). Continuous measurements of ammonium along the core revealed long-term changes of ammonia emissions from soil and vegetation in the Northern Hemisphere (Fuhrer et al 1996). Temperature changes, identified primarily by isotope measurements, are therefore reinforced by the additional information linked to biogeochemical cycles. This is particularly important in the Northern Hemisphere where seesaw processes are observed. The concentration of compounds like methane, which depends mainly on soil humidity (Blunier et al 1995), astonishingly mimics temperature variations (Chappellaz et al 1993, figure 5). The concentration of formate seems to be closely linked with the extent of vegetation at mid to high northern latitudes (Legrand and De Angelis 1995).
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Figure 4. Comparison of the water isotope records in the deepest part of GRIP and GISP 2 ice cores (from Jouzel et al 1994). Discrepancies appear below 2700 m depth (note that the depth scales are slightly shifted for a better comparison of the profiles). Hatched areas correspond to depths for which tilted ice layers are observed. A rapid climatic event is recorded at about 2790 m (GRIP project members 1993).

Regarding marine biogenic activity, sulfate and methanesulfonate (MSA) measurements are not in agreement with Antarctic data. In particular, high MSA values are not observed in glacial conditions (Mayewski et al 1994; Legrand et al 1997). Marine biogenic activity, responsible for the relatively high sulfate content of Antarctic precipitation, has a weaker influence in the North. On the other hand, volcanic sulfate is probably a more important contribution in Greenland than in the Antarctic. Eruptions of global concern have been detected by ECM along the Eurocore and GRIP cores at Summit (Clausen et al 1995) as well as on the GISP core (Zielinski et al 1994). More intense volcanic activity seem to follow the glacial/interglacial transition.

Very large amounts of alkaline dust were transported in the glacial atmosphere and deposited in Greenland. This is a confirmation of previous studies at Camp Century and Dye 3 (Cragin et al 1977). Sr and Nd isotope measurements (Biscaye et al 1997) indicate that LGM dust originates from East Asia. This suggests that the general atmospheric circulation was most probably shifted southward by the considerable expansion of the Laurentide ice sheet during the ice age (Mayewski et al 1994). This dust input changes markedly the chemical and physical properties of the ice corresponding to cold periods. It can be deduced from these observations that the general chemical properties of the northern hemisphere atmospheric aerosol were also significantly different from those of the present. The only major species which does not exhibit concentration changes over climatic stages in Greenland is nitrate. Up to now, no plausible explanation has been proposed for explaining this peculiar feature of nitrate deposition.

Detailed 10Be measurements along the GRIP core (Yiou et al 1997) have shown that concentration changes of this cosmogenic radioisotope are primarily linked to snow accumulation changes, as in Antarctica. However, a solar and geomagnetic modulation is also detected, as also possibly primary cosmic ray variations. The most recent of the two peaks found in the Vostok core is well recorded in GRIP about 38 ka B.P.
Figure 5. GRIP ice core: methane concentration changes (in ppbv with error envelope) remarkably mimic the typical seesaw climatic profile ($\delta^{18}O$ in %) observed for the last 40 ka (from Chappellaz et al 1993).

4. Changes due to anthropic activities

We will examine separately the cases of global and hemispheric pollutions (long-lived and short-lived species, respectively).

4.1 Long-lived species

The atmospheric concentrations of several long-lived trace gases are currently increasing due to anthropogenic emissions. Monitoring programmes to document these trends started only recently. Consequently, ice core data are invaluable for reconstructing the pre-industrial levels and documenting in detail the sources and sinks controlling their atmospheric concentrations. In particular, the concentration changes of greenhouse gases are clearly recorded in the air bubbles encapsulated in ice from both polar regions. The studies are now extending back to the last millennia, in order to better define the natural variability in
past climatic conditions, characterize the very beginning of the anthropogenic impact and assess the interhemispheric difference.

Greenhouse-gas concentrations over the last thousand years are shown in figure 6. In Greenland, pre-industrial concentrations of CO2 (Barnola et al. 1995) and CH4 (Blunier et al. 1993; Nakazawa et al. 1993) during the 18th century are found to be 280 and 0.73 ppmv (0.67–0.68 in Antarctica), respectively. During the last millennium, prior to the 17th century, CO2 concentrations show fluctuations in the range 275–285 ppmv.

Note that detailed descriptions of the CO2 and CH4 concentration increases linked to human activity have been obtained at Law Dome, a very high accumulation coastal Antarctic site (Etheridge et al. 1992; Etheridge et al. 1996).

It is important to emphasize that: 1) the present-day greenhouse-gas concentrations are outside the range of natural variation reconstructed from ice core studies, and 2) the changes due to human activities have occurred in less than two centuries, contrary to natural ones which take millennia. This is illustrated by figure 3: the co-variation of the CO2 and CH4 concentrations have been radically modified when passing from pre-industrial (the last 220 ka) to industrial conditions (the last two hundred years). It is amazing that the increases of the atmospheric concentration of these two gases are so tightly linked for the industrial period; their anthropogenic origins and sinks are quite different. A reason for the observed correlation could just be their dominant link to global population growth.

Figure 6. Carbon dioxide concentrations over the last 1000 years measured in Greenland ice cores (Eurocore and GRIP) by two different laboratories: LGGE Grenoble (squares) and Physikalisches Institut Bern (solid circles). Antarctic profile (continuous line) was obtained from Antarctic ice cores. Figure modified from Barnola et al. 1995.

Figure 7. Non-sea-salt sulphate concentration changes since 1860 A.D. at Summit (Greenland; Legrand et al. 1997) and at South Pole (Kirchner 1988). Dating of snow layers at South Pole may be uncertain by a few years between the two volcanic markers Krakatau (KR 1883, recorded in both polar regions) and Agung (AG 1963, recorded at South Pole only). Anthropogenic pollution is recorded only in Greenland and visible from about the turn of this century.

4.2 Short-lived species

For species having atmospheric residence times of the order of weeks to months, the impact of pollution is limited to the hemisphere where the pollutants are emitted.

The cases of sulphate and nitrate in Greenland were documented for more than a decade (Neftel et al. 1985; Mayewski et al. 1986). More detailed measurements have been performed in Greenland during the Eurocore, GRIP and GISP2 operations at Summit. As an example, the GRIP sulphate profile of the last 150 years, compared to the South pole sulphate record, is presented in figure 7. It shows that the anthropogenic contribution started to be significant during the first decade of this century, but the record is blurred by several volcanic eruptions having occurred at that time. At present, since about 20 years, this pollution shows a decreasing trend due to measures taken to reduce the sulphur content of fossil fuels. At South Pole, only natural fluctuations are recorded. Nitrate exhibits a steadily growing trend since about forty years, in relation with the still rising NOx northern hemisphere emissions but this record could be different from the true atmospheric variations due to possible post-deposition changes affecting this gaseous species in the firn. Unfortunately, the ice does not record all the species that would be required to fully estimate the oxidation capacity of the past atmosphere, in particular the most important ones O3 and OH radical, except H2O2 (Neftel et al. 1984; Sigg and Neftel 1991;
Anklin and Bales 1997). On the other hand, related species CO (Haan et al 1996), HCHO (Staffelbach et al 1991) and overall CH4 (Khalil and Rasmussen 1985; Khalil and Rasmussen 1989; Raynaud et al 1993) and NO3 (see above) are now available with a variable degree of confidence for the pre-industrial and industrial times.

Metals such as Pb, Cu, Zn, Cd, Hg are naturally present in primary aerosol (mainly continental dust). They may have a gas-derived aerosol fraction linked to biological processes. These metals, in particular atmospheric lead produced from alkyl Pb additives used as antiknock agents in automobile and aircraft gasoline, have been intensively studied in polar snow in relation with ecological and health problems they can cause on a local scale. Surprisingly, this type of pollution is not recent: the analysis of the upper part of the GRIP ice core demonstrated that mining activities during Greek and Roman times have had also a marked influence on the atmospheric cycle of lead (Hong et al 1994) and copper (Hong et al 1996a). Regarding the intrinsic level of this pollution, it can be shown (figure 8) that very high values were already reached during the ice age, quite comparable to anthropogenic levels, due to enhanced crustal dust transport to Greenland in very cold climatic conditions. Isotope measurement is a powerful tool to unravel the respective contributions of the various source regions of this metal (Rosman et al 1993). The identification of automobile lead was reinforced by subpicogramme level analysis of the degradation products of organolead compounds (Lobinski et al 1993).

5. Concluding remarks

This paper must be considered as a general rapid survey of the palaeoenvironmental information which has been extracted from recent polar ice cores. Only the most striking features have been reported.

Recent ice core data obtained in Antarctica (Vostok) and Greenland (Summit cores) have made it possible to investigate the teleconnections existing between climate changes in the Northern and Southern Hemispheres and therefore to better understand the climatic system on the global scale. In addition to climatic parameters, polar ice provides additional information linked to the continental and marine atmospheric environments.

This effort must be amplified, since polar regions, in particular the Antarctic, are composed of distinct geographical areas representative of various climatic zones. It could be mentioned also that the Holocene time period is relatively less documented than the last ice ages. The study of just one or two ice cores is insufficient to picture with certainty the situation prevailing over a whole polar ice sheet. International deep drilling operations are currently being developed at several Greenland (e.g. North-GRIP) and Antarctic (EPICA [European Project for Ice Coring in Antarctica, Lorius and Jouzel 1996] in East Antarctica, WAISCORE [West Antarctic Ice Sheet CORE] in West Antarctica, Dome Fuji etc.) sites for a better coverage of these vast remote continents.

Some pending questions should be further investigated: a typical example is the nature and origin of nitrate in polar regions. Nitrate is a major constituent of polar ice impurities. Moreover, this compound is linked to the oxidation capacity of the atmosphere. In addition, ice core research should be aimed at two immediate goals: 1) a better understanding of the transfer function linking ice records to atmospheric composition, and 2) an increase of the number of compounds or elements determined in the ice samples.

1. On the Central Antarctic Plateau, where several ice coring operations have been carried out or are being planned for future, marked postdeposition effects have been discovered recently for atmospheric acid gases like HCl, HNO3, and MSA (Wagnon et al in press), making the current interpretation of ice core data of these species uncertain. Laboratory experiments are also recommended to investigate the physico-chemical interactions between gaseous species and ice surfaces at low temperature. Regarding CO2, there are still discussions about the accuracy of the ice records, in particular for Greenland ice where air bubble composition may be slightly modified in depth. More work is in progress about this critical issue.

2. The determination of a larger number of trace species in polar ice is possible, using the new and
powerful analytical techniques such as liquid or gas chromatography, or mass spectrometry (e.g. ICP-MS, GC-MS). In addition to major greenhouse gases, other gases should also be investigated, e.g. hydrocarbons involved in the tropospheric ozone formation or OCS, a major gaseous species of the atmospheric sulphur cycle.

The organic fraction of the impurities deposited in ice is a domain which is nearly unexplored: organic compounds could be used to document marine and continental biogenic activity in past climatic conditions.

Polar ice has already provided invaluable information about the global climatic system, but not yet revealed all its secrets.

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