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Environmental records from polar ice cores

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Polar ice cores provide a wide range of information on past atmospheric climate (temperature, precipitation) and environment (gas and aerosol concentrations). The dating can be very accurate for the more recent part of the records but accuracy decreases with depth and time. Measurements of cosmogenic isotope concentrations (such as ^{10}Be) provide information on palaeo-precipitation rates and particular events can be used to correlate ice core records. Besides these climatic applications, ^{10}Be concentration records in ice cores also contain information on solar activity changes.

Introduction

The recovery of records of the environmental history is one of the keys to a better understanding of climatic changes. In this respect polar ice can provide a wide range of information, as it records atmospheric climatic conditions and samples aerosols and gases in consecutive datable layers over timescales extending to 150000 years before present (BP). In particular, changes in cosmogenic isotope concentration can potentially provide information on production rates that are influenced, among other factors, by solar modulation. This latter aspect is discussed in this Symposium by Dr G. M. Raisbeck and Professor H. Oeschger.

The atmospheric record

Although we cannot expect to find an ideal climatic recorder in nature, glacial ice is proving to be a rather remarkably close approximation to it (Lorius 1990; Dansgaard & Oeschger 1989).

The basis for palaeotemperature reconstruction is the existence of current correlations between the proportion of deuterium to hydrogen and ^{18}O to ^{16}O atoms measured in deposited snow and temperature conditions at the site, resulting from fractionation processes that take place in the atmospheric water cycle. Although the isotopic composition of polar snow depends on several parameters, there exists a linear relation in both of the polar ice sheets, between the mean annual surface temperature and the mean δ^{18}O of δD value of deposited snow (Lorius & Merlivat 1977; Johnsen *et al.* 1988) and the large isotopic changes (i.e. glacial–interglacial) obtained from ice cores can be interpreted, as a first-order approximation, in terms of local atmospheric temperature changes. However, the climatic signal:noise ratio leads to more unfavourable conditions for the quantitative reconstruction of climatic changes of smaller magnitude such as that which prevailed over the past centuries.

Relating gas concentrations obtained from ice-core extraction to atmospheric values that are of global significance is much more straightforward; although precipitation mechanisms may have secondary effects, there is for instance, within the precision of the measurements, no

differences between the CO_2 and CH_4 greenhouse gas data monitored by modern observations and those obtained from corresponding polar ice layers (Siegenthaler & Oeschger 1987; Stauffer *et al.* 1985).

Such precipitation mechanisms are of importance to establish a quantitative link between the concentration of aerosols and impurities in surface snow (Davidson 1989). Although there is no doubt that the concentration of a species in the air is reflected in snow deposits at the site, there is a lack both of direct observations and in understanding aerosol deposition processes. The relative contribution of 'wet' (including precipitation scavenging) and 'dry' deposition is poorly known and may vary with location and possibly with time. Concentration of impurities in ice, including cosmogenic isotopes may then depend on several factors such as source intensity or production rate but also on atmospheric circulation and rate of snow precipitation.

An overview summarizing the climate-related information which can be obtained from ice cores is given in table 1.

TABLE 1. SHORT SUMMARY OF ENVIRONMENT INFORMATION AND CORRESPONDING ICE-CORE SIGNAL

atmosphere	ice core
temperature	D/H, $^{18}O/^{16}O$
precipitation	D/H, $^{18}O/^{16}O$, ^{10}Be
humidity	D/H, $^{18}O/^{16}O$
aerosols	
natural (continents, sea volcanoes, biosphere)	chemicals (Al, Ca^{2+}, Na^+, H^+, SO_4^{2-}, NO_3^-)
man made	SO_4^{2-}, NO_3^-, Pb, radioactive fallout
cosmogenic	^{10}Be, ^{26}Al, ^{36}Cl
circulation	particles
gases: natural and man made	O_2, N_2, CO_2, CH_4, N_2O

TIMESCALES

For the upper part of the ice sheets the accuracy of the chronology can be very high. Annual layers can be counted from seasonal variations of various parameters such as visual stratigraphy, physical properties, isotopic composition, electrical conductivity, chemicals, etc., but at great depth they are becoming indiscernible. Prominent features found in ice cores can be used as reference horizons. They can provide ages when causal events are documented (radioactive fallout from nuclear tests over the past decades, ash or aerosol deposits from volcanoes); more generally, large-scale atmospheric events can be used for relative intercomparison between ice cores (see for instance below the use of ^{10}Be peaks to correlate antarctic ice records), or with other palaeodata such as those from sea, land or lake sediments. Although there are promising possibilities to obtain absolute ages for ice-core records from radioactive and other dating techniques long-term timescales have been so far based on numerical modelling of the age distribution through ice sheets by ice dynamics (Reeh 1989).

The accuracy of the method depends on a number of factors, but change in accumulation rate is the most important parameter to consider.

Cosmogenic isotopes: the ^{10}Be records

A number of long-lived radioactive nuclides are formed by cosmic-ray-induced nuclear reactions in the atmosphere. These 'cosmogenic' isotopes are then either transported to ice surfaces in precipitation or dry fallout (for non-volatile species such as ^{10}Be, ^{26}Al, ^{36}Al) or occluded, along with trapped air in bubbles (^{14}C). These isotopes have two potential applications in ice core studies: (i) they might possibly be used to 'date' (either in an absolute, or relative way) ice cores, (ii) they might give a time record of the cosmogenic production rate.

The first application may be illustrated by evaluation of past accumulation (precipitation) changes in Antarctica on a glacial–interglacial timescale. One approach is based on the fact that current accumulation rates in Antarctica are governed by the amount of water vapour circulating above the inversion layer. This amount is itself controlled by temperature via the saturation vapour pressure and the isotope-based temperature record can thus be used to estimate past accumulation. Results give quite similar accumulation values during interglacials while precipitation appears to have been reduced to about 50% the current value during the coldest periods of the ice age. A second approach (Yiou *et al* 1985) is based on ^{10}Be measurements performed along an ice core. Concentrations of this long-lived cosmogenic radioisotope are quite similar during the two interglacials; they increase during colder periods, by up to a factor of 2 during full glacial conditions. Assuming a constant ^{10}Be deposition flux, the measured concentrations are reflecting the amount of snow precipitation. Indeed there is a very good agreement between accumulation rates derived independently from the isotope temperature and ^{10}Be records. The coherence of these results lends some support to this estimate of past precipitation and also indirectly further supports possible reasons why ^{10}Be concentration might be inversely correlated with palaeoprecipitation rate.

Furthermore ^{10}Be peaks have been found around 60000 and 35000 years BP in Antarctica ice (Raisbeck *et al.* 1987) not correlated with any obvious climatic feature and it was suggested that these peaks may be due to increased production in the atmosphere. There are three possible causes for such production changes: variations in primary cosmic ray flux, changes in solar modulation or changes in geomagnetic field intensity. But regardless of the final explanation these peaks have been used as stratigraphic markers to correlate various climatic records from Antarctic ice (Jouzel *et al.* 1990).

Over shorter timescales (centuries) ice core ^{10}Be and isotope temperature records can be used to test the influence of solar variability on climate (G. M. Raisbeck *et al.*, this Symposium) and ^{10}Be concentrations in ice cores can be compared with the ^{14}C variations in tree rings (H. Oeschger, this Symposium). As already pointed out there may be some limitations in the quantitative reconstruction of relatively small climatic changes from the ice-core isotopic record while on the other hand ^{10}Be concentrations may then more favourably reveal solar variability features than in long-term glacial–interglacial records.

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