International Effort Helps Decipher Mysteries of Paleoclimate From Antarctic Ice Cores

ICE CORES DRILLED AT VOSTOK STATION, ANTARCTICA, AND STUDIED OVER THE PAST 10 YEARS BY RUSSIA, FRANCE, AND THE UNITED STATES (FIGURE 1) ARE PROVIDING A WEALTH OF INFORMATION ABOUT PAST CLIMATE AND ENVIRONMENTAL CHANGES OVER MORE THAN A FULL GLACIAL-INTERGLACIAL CYCLE. THE ICE CORES SHOW THAT EAST ANTARCTICA WAS COLDER AND DRIER DURING GLACIAL PERIODS THAN DURING THE HOLOCENE AND THAT LARGE-SCALE ATMOSPHERIC CIRCULATION WAS MORE VIGOROUS DURING GLACIAL TIMES. THEY ALSO SUPPORT EVIDENCE FROM DEEP-SEA SEDIMENT STUDIES FAVORING ORBITAL FORCING OF PLEISTOCENE CLIMATE, REVEAL DIRECT CORRELATIONS OF CARBON DIOXIDE AND METHANE CONCENTRATIONS WITH TEMPERATURE, AND INDICATE HOW THE ACCUMULATION OF TRACE COMPOUNDS HAVE CHANGED THROUGH TIME.


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Interpreting Paleoclimate From Ice Cores

Due to fractionation processes, there is a progressive depletion of the deuterium and oxygen 18 content of the precipitation formed in a given airmass. In polar regions, this fractionation results in a linear relationship between the average isotopic content of
snow and the mean annual temperature. This empirical relationship—illustrated by atmospheric circulation models—allows us to reconstruct local records of temperatures from the isotopic content of ice: in Antarctica, a cooling of 1°C—the atmospheric temperature above the inversion layer where precipitation are formed—results in a decrease of 9 per mil deuterium.

An accurate chronology is essential for interpreting ice core paleoclimate data. At Vostok, accumulation is too low for recognizable annual signals to form, so we developed a chronology combining an ice flow model and an accumulation model that accounts for the fact that accumulation was lower during colder periods and vice-versa. Because the accumulation rate is governed by saturation water vapor pressure, past accumulation may be estimated from the temperature record. Accumulation rates inferred in this way are supported by measurements of 10Be in Vostok ice. Deposition of this cosmogenic isotope is assumed to be constant. Lorius et al. [1985] established the chronology down to 2083 m (age of 164 kyr BP). This chronology was revised (revised age of 156 kyr BP at this depth) and extended down to the deepest part of the 4G core (2546 m) dated at 220 ± 20 kyr BP [Jouzel et al., 1993].

The combined deuterium record from the 3G and 4G cores is shown in Figure 2. The record shows the last two glacial-interglacial transitions with atmospheric temperature changes of ~6°C. The last ice age is characterized by three minima separated by slightly warmer episodes, which are called interstadials. The penultimate glacial is characterized by a long cold period with smaller amplitude of variation than that of the last ice age. This record is marked by a strong obliquity component (period of ~41 kyr resulting from changes in the tilt of the Earth) and weaker but significant precession components (periods of 23 and 19 kyr associated with the wobble of the axis), further supporting the role of orbital forcing in the Pleistocene glacial-interglacial cycles demonstrated by deep-sea core records.

There is additional support for the above chronology of the Vostok ice core derived from a glaciological model. Southern Ocean temperature variations correlate with those at Vostok. Also, the variations in δ18O of O_2 in air trapped in the Vostok ice [Sowers et al., 1993] roughly coincide with variations in δ18O of seawater reflected in the isotopic content of the forams in deep-sea sediments. This comparison is based on the fact that photosynthesis transmits seawater variations to atmospheric O_2. There is also a good correlation between the Vostok dust concentration and the record of mass accumulation rate in the RC27-61 Indian Ocean core [Jouzel et al., 1993].

Beyond their use as correlating and dating tools, each parameter conveys specific geochemical information. Variations in 10Be concentrations are caused by factors other than accumulation changes. The existence of 10Be peaks around 35 and 60 kyr BP have been attributed to increases in production of this cosmogenic isotope [Raisbeck et al., 1987]. The δ18O of O_2 record also contains information about fractionation by biogeochemical and hydrologic processes. Similarities between Vostok and Southern Ocean temperatures indicate that the Vostok record is representative of a large geographical extent, while the general qualitative agreement with the δ18O of deep-sea core suggests that the main broad features of this record are somewhat global in character.

The changes in terrestrial aerosols [Petit et al., 1990] contain climate-related information. Greater dust concentration during full glacial periods than during interglacials probably indicates that glacial periods were characterized by more extensive deserts, more intense surface winds in the desert source regions, and/or more efficient meridional transport. This idea of stronger circulation during glacial periods is reinforced by the fact that glacial values of marine aerosols are much higher than interglacial levels.

Another important aspect of change in the past atmosphere's aerosol load is a secondary aerosol composed of the nonsea salt sulphate and methanesulphonic acid (MSA), an oxidation product of dimethylsulfide (DMS) emitted by marine biogenic activity. Although studies based on MSA measurements show that the link between climate and biogenic marine activity could be more complex than initially thought, both non-
Air Sampling

Air initially enclosed in Vostok ice provides our only record of variations in the atmospheric concentrations of CO₂ and CH₄ over a complete glacial-interglacial cycle [e.g., Raynaud et al., 1993]. For both greenhouse gases, concentrations are higher during interglacial periods than during full glacial periods. Since preindustrial times, levels of CO₂ and CH₄ have increased by about respectively 40% and a factor of 2. A close correlation between these gas concentrations and the Vostok isotopic temperature has been confirmed by extending the record over part of the previous cycle [Jouzel et al., 1993]. However, at the end of the last interglacial, the CO₂ decrease significantly lags the Antarctic cooling, while CO₂ and Antarctic temperatures increase in concert during the warmings corresponding to the glacial-interglacial transitions. Interestingly, at least during certain deglaciation periods, the trace-gas increase precedes—by several thousands of years—the onset of most melting of the northern ice sheets.

From a climatic viewpoint, CO₂ and CH₄ have played an important role. Together with the growth and decay of the Northern Hemisphere ice sheets, these greenhouse gases have amplified the initial orbital forcing and they account for about half of the glacial-interglacial climate changes. As for climate sensitivity, these data suggest that positive feedbacks operate in the climatic system and support the idea that significant greenhouse warming will occur in the next century [Raynaud et al., 1993].

Ice sheet modeling is used to date ice cores and study long-term interaction between climate and the dynamics of large ice sheets [Salamatin, 1992]. Information gained from studies of ice texture and fabric [Lipenkov et al., 1989], ice rheology, and ice densification is central to this objective. Models predict that ice sheet over Vostok will thin during cold periods. In agreement with this, the long-term trends of total air content in the ice show that during colder periods air pressure was higher which well supports the idea that elevation of the ice sheet was lower. Other studies confirm that microorganisms—including species that have disappeared elsewhere—could survive in the deep Antarctic ice for many thousands of years following anabiosis.

Sample Analysis—Exciting Results

In France and the United States, analysis of samples of the last 200 m of core 5G are nearly complete and exciting results have been forthcoming. Figure 2 shows a first set of deuterium data from the bottom part of this core, a discontinuous series of 27 samples every 10 m or so. The timescale has been extended back to 2755 m giving an age of 260 kyr BP (±10%).

Although the chronology is preliminary, we note that the correspondence with the δ¹⁸O of oceanic record of ice volume, relatively easy to establish back to the penultimate glacial, is not straightforward for the earlier part of the record because the uncertainty in ages increases with time in the past.

Jouzel et al. [1993] suggest that the bottom of core 4G (2546 m) reached back to cold marine stage 7.4 (around 220 kyr BP). If we accept this age, then we would associate the subsequent isotopic temperature maximum at ~2620 m depth with stage 7.5. Stage 7 at Vostok would then be much shorter than the oceanic record indicates, and the isotopic temperature maximum at the very bottom of the core would correspond to stage 9. This chronology is problematic. It is more likely that the bottom of core 4G—2546 m deep—may correspond to stage 7.2, which suggests that the deepest 5G samples correspond to 7.5.

Figure 2 also shows electrical conductivity measurements (ECM) performed in the field to search volcanic events and study change in the background signal. We can assume that the change of the impurity content associated with climate changes modifies the ice acidity (SO₄, NO₃, CI) and thus electrical conductivity. For the bottom part of the core below 2500 m, a link with isotope content is observed, which supports the use of ECM as an additional climatic indicator.

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References