level), more intense surface winds in the source regions, and/or more efficient meridional transport at the times of glacial maxima (Petit et al., 1999). The close linkage between climate and CO_2 and CH_4 concentrations documented in the Vostok core throughout the four climatic cycles supports the role of the greenhouse gases as amplifiers of initial orbital forcing.

The sequence of events during glacial terminations suggests that increases in Antarctic air temperature and atmospheric greenhouse gas concentrations lead sea level rise (Northern Hemisphere deglaciation) by a few thousands of years (Petit, et al., 1999, Sowers et al., 1991, Shackleton, 2000). It has also been shown that CH_4 (Delmotte et al., 2004) and CO_2 (Caillon et al., 2003; Fischer et al., 1999; Petit, et al., 1999; Pépin, et al., 2001) concentration increases lagged Antarctic warming by several hundreds of years. This natural scenario is, however, different from the present situation, where rise of greenhouse gases, as a result of anthropogenic activities, has been imposed first. The reconstructed record for MIS 11 indicates that concentrations of CO_2 and CH_4 throughout this 30-kyr-long interglacial period, which is considered an "orbital" analog for the Holocene, were close to the pre-industrial levels and lower than during MIS 9.3 (Raynaud et al., 2005). Thus, the present-day increase in concentration of these greenhouse gases in the Earth's atmosphere seems to have been unprecedented during the past 440 kyr.

Project facts

Project: Vostok ice core project
Contact: Vladimir Lipenkov, lipenkov@aari.nw.ru
Participants: Institutes and laboratories in Russia (AARI of Roshydromet; St. Petersburg Mining Institute; Institute of Microbiology, RAS; Kazan State University; Institute of Geography, RAS), in France (LGGE, CNRS, Université Joseph Fourier, Grenoble; Laboratoire des Sciences du Climat et de l'Environnement, CNRS-CEA, Saclay) and in the United States (laboratories funded by NSF).
Funding: The Vostok venture was made possible by the logistical support of Russian Antarctic Expedition (RAE), Institute Francais pour la Recherche et la Technologie Polaires (IFRTP) and the Office of Polar Programs (NSF). The development of drilling technology and the ice-core studies were funded by national contributions from Russia, France and the United States.
Where: East Antarctica (78°28'S, 106°48'E, altitude 3488 m asl, ice thickness 3750 m)
When: 3 main deep holes (3G, 4G, 5G) were drilled from 1980 to 1998. The ice core analyses are in progress.
What: 3 ice cores reaching depths of 2202 m, 2546 m and 3623 m. High-resolution records of atmospheric composition and climate covering the last 440 kyr.
Database: www.ncdc.noaa.gov/paleo/icecore/antarctica/vostok/vostok.html

Ongoing ice core studies

Studies of the Vostok ice are now focused on the deepest section of the core, below 3310 m. The extrapolation of the Vostok timescale to greater depths, made with the aid of an ice-sheet flow model, shows that the age of glacial ice just above its contact with accretion lake ice (at a depth of 3530 m) may reach ~2000 kyr (Salamatin et al., 2004). We hope that the joint effort of scientists working in the fields of paleoclimate records and physical properties of ice will allow us to decipher information on some of the earlier climatic cycles archived in this section of the Vostok core. Meanwhile, comprehensive analysis of the now available accretion ice from depths below 3539 m is expected to provide a clue to understanding the extraordinary environment of subglacial Lake Vostok.

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For full references please consult:
www.pages-igbp.org/products/newsletters/ref2006_1.html

European Project for Ice Coring in Antarctica (EPICA)

Eric Wolff[1] on behalf of the EPICA community
[1]British Antarctic Survey, Cambridge, UK; ewwo@bas.ac.uk

Introduction

The last few hundred thousand years form the context in which we can learn how the Earth System (including its climate) works. Although the geological setting of the Earth was similar to today, very significant changes occurred in the climate, the circulation of the ocean, and the composition of the atmosphere. By learning about these changes, we can understand the processes that can occur, and that should be represented by models—the same models that will be used to predict future conditions.

Ice cores are particularly powerful because numerous climate responses and forcings (including greenhouse gas concentrations) are recorded in the same core. In early Antarctic cores covering complete glacial-interglacial cycles (notably Vostok and Dome Fuji), we were able to see the close connection between climate and greenhouse gas concentrations that prevailed through four glacial-interglacial cycles over the last 400 kyr (Petit et al., 1999, Watanabe et al., 2003).

Fig. 1: Dome C drilling location on the East Antarctic Ice Sheet (75°06'S, 123°21'E, altitude 3233 m asl) as viewed from the air (Photo Borek Air, PNRA/EPICA).

Greenland ice cores (e.g. North Greenland Ice Core Project Members, 2004) most clearly revealed the importance of abrupt climate changes, probably resulting from changes in ocean heat transport, during the last climatic cycle.

The aim of EPICA was to drill two cores to bedrock in East Antarctica. At Dome C, the target was old ice; in Dronning Maud Land (DML), the aim was to obtain a South Atlantic counterpart to the high-resolution Greenland records, covering at least one climatic cycle. The drilling at Dome C (Fig. 1) is complete and the ice contains a record of 800 kyr of climate. At the time of writing, the drilling at DML was very close to the bed, and contained one climatic cycle at high resolution and probably several more at lower resolution.

Eight glacial cycles in an ice core

The records from Dome C show that the top 2770 m of ice correspond to the "Vostok" time period and nearly 500 m of older ice is below that. The initial timescale (EDC2) for Dome C was obtained using an ice flow model constrained by a small number of control ages. There are obvious similarities and differences between the resulting climate record and marine records. The bottom of the data published so far (EPICA Community Members, 2004) is at about 740 kyr BP, in the cold marine isotope stage (MIS) 18.4, although we are confident that we have a good climate record back as far as 800 kyr BP (MIS 20.2).

The ice core record now extends through eight glacial cycles and is dominated by the 100 kyr cyclicity characteristic of the late Quaternary period. This is seen both in the temperature proxy (deuterium), and in physical and chemical measurements (such as dust and sea salt) that represent different aspects of the environment (Fig. 2). However, the "pre-Vostok" cycles are distinctly different from the later ones. Interglacials have a much lower amplitude before about 450 kyr BP but appear to span a longer period in each cycle. This characteristic is also apparent in marine records but is more pronounced in the ice core record. There is no obvious external forcing responsible for such a change, however many of the internal feedbacks in the system reflect it. For example, both CO_2 (Siegenthaler et al., 2005) and CH_4 (Spahni et al., 2005) are at lower concentrations in the early interglacials. The close correspondence between CO_2 and Antarctic temperature persists throughout the record.

One other early focus of the Dome C core was MIS11. This period is often seen as an analog for the present and near future (in the absence of anthropogenic influence) because the orbital forcing of climate is similar in the two periods (with low eccentricity and hence weak precessional forcing). Although we can discuss how to align the climate records from the two periods, it is true that MIS11 was a very long interglacial: 28 kyr, using a definition that makes the Holocene 12 kyr old so far. If this is a better analog than more recent short interglacials, then the "natural" Holocene would still have a long course to run.

The Atlantic sector of the Southern Ocean

The current snow accumulation rate is 2-3 times higher in DML than at Dome C and, consequently, the last climatic cycle is found at much better resolution there. Annual layers can still be observed even in the glacial ice, and the difference between the age of the ice (containing the climate record) and that of the air bubbles (containing the greenhouse gas record) is relatively small. This should allow us to link the Antarctic records with the sequence of rapid climate changes (Dansgaard-Oeschger (D-O) events) seen in Greenland cores, with only a small time uncertainty. It already appears that every D-O event found in Greenland has a counterpart in the Antarctic records, and learning about the relative phase and amplitude of the Greenland and Antarctic events will be critical in distinguishing between mechanisms and in testing models. The differences in response across the continent of Antarctica will also be of great interest, since although the deuterium (temperature) records have great similarities at Dome C and DML, there are big differences in the magnitude of concentrations of chemical species at the two sites.

Continuing analysis

While the EPICA drilling operations are essentially complete, much remains to be done in

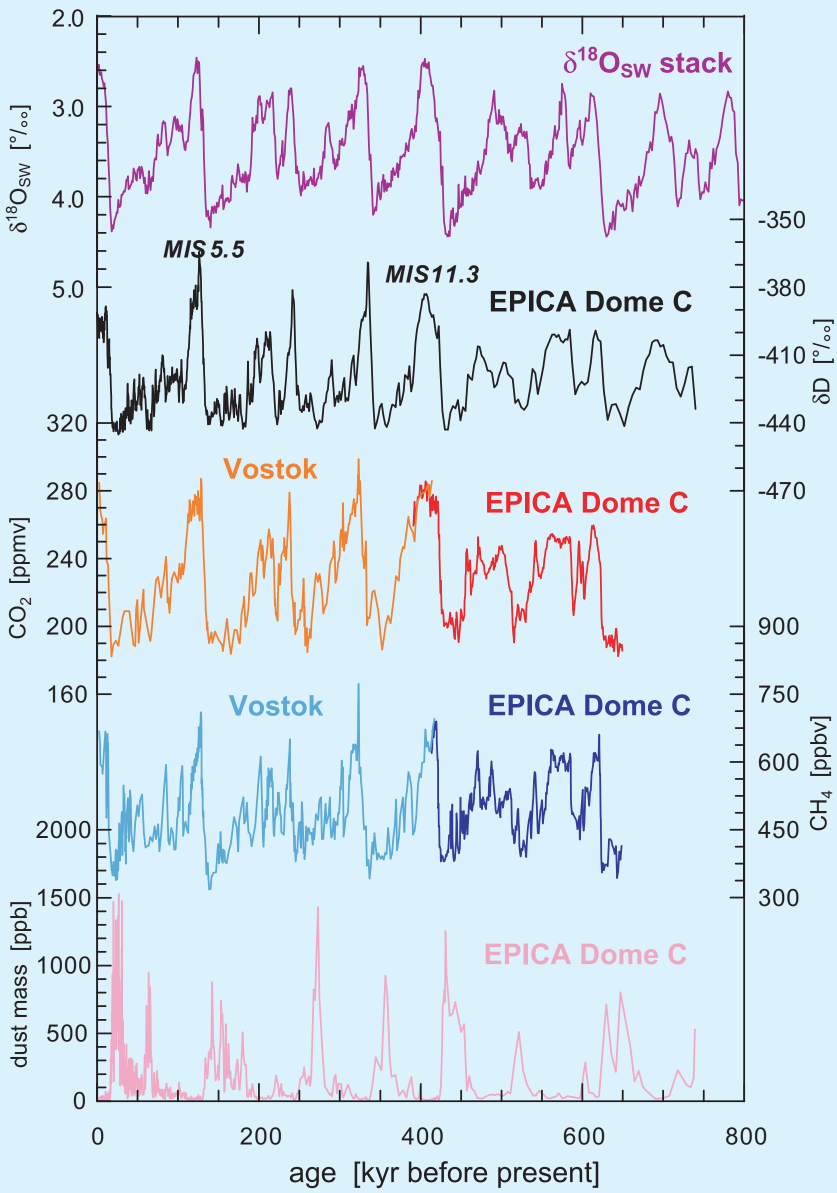

Fig. 2: Ice core parameters over 740 kyr, along with the recently compiled benthic marine oxygen isotope record (Lisiecki & Raymo, 2005). The Dome C δD and dust data are on the EDC2 timescale (EPICA Community Members, 2004) and the marine data on the LR04 timescale. CO_2 and CH_4 data are from Dome C (Siegenthaler et al., 2005; Spahni et al., 2005) and Vostok (Petit et al., 1999). MIS 5.5 and 11.3 are marked to provide reference points.

analysis and interpretation of the cores. EPICA has given us the first glimpse of an earlier period of Earth history, and the chance to compare behavior across the vast continent of Antarctica throughout a glacial cycle. Intensive work is now underway to provide the extended record from Dome C and the high-resolution record from DML. We will use additional parameters, such as particulate and dissolved aerosol species in the ice, to define the climate, and use the detail of the two records to understand variability. Further work will help us to elucidate the underlying mechanisms governing the highly variable behavior of the Earth System.

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Project facts

Project: European Project for Ice Coring in Antarctica (EPICA)

Contact: Eric Wolff, ewwo@bas.ac.uk

Participants: Numerous scientists from laboratories in 10 European nations, under the auspices of the European Science Foundation (ESF) and European Union (EU).

Funding: Funded by the EU (EPICA-MIS) and by national contributions from Belgium, Denmark, France, Germany, Italy, The Netherlands, Norway, Sweden, Switzerland, and the U.K. The science was made possible only by the efforts particularly of the French (IPEV) and Italian (PNRA) logistic agencies for Dome C, the Alfred Wegener Institute in Germany for DML, and the drilling teams led by Laurent Augustin (Dome C) and Frank Wilhelms (DML).

Where: East Antarctic Ice Sheet (Dome C: 75°06'S, 123°21'E, altitude 3233 m asl, ice thickness ~3270 m; DML: 75°00'S, 0°04'E, altitude 2892 m asl, ice thickness ~2780 m).

When: Drilling: 1996-2006 (survey work predates this and analysis continues).

What: 2 deep ice cores to bedrock, multi-parameter analysis

Web Page: www.esf.org/esf_article.php?activity=1&article=85&domain=3

Databases: www.pangaea.de/Projects/EPICA/ www.ncdc.noaa.gov/paleo/icecore/antarctica/domec/domec_epica_data.html