investigations within the METRO project is much improved, and the data can ultimately be integrated in regional geological and ecological studies of deep-sea environments. Within the METRO project, the methane concentrations and fluxes in the sediments and into the ocean from such sites through controlled degassing studies of autoclave cores, through gas desorption experiments, and through geochemical flux measurements will be studied in future cruises. These findings can then be integrated with the results of geoacoustic mapping of the cold seep sites in order to derive better regional methane flux estimates.

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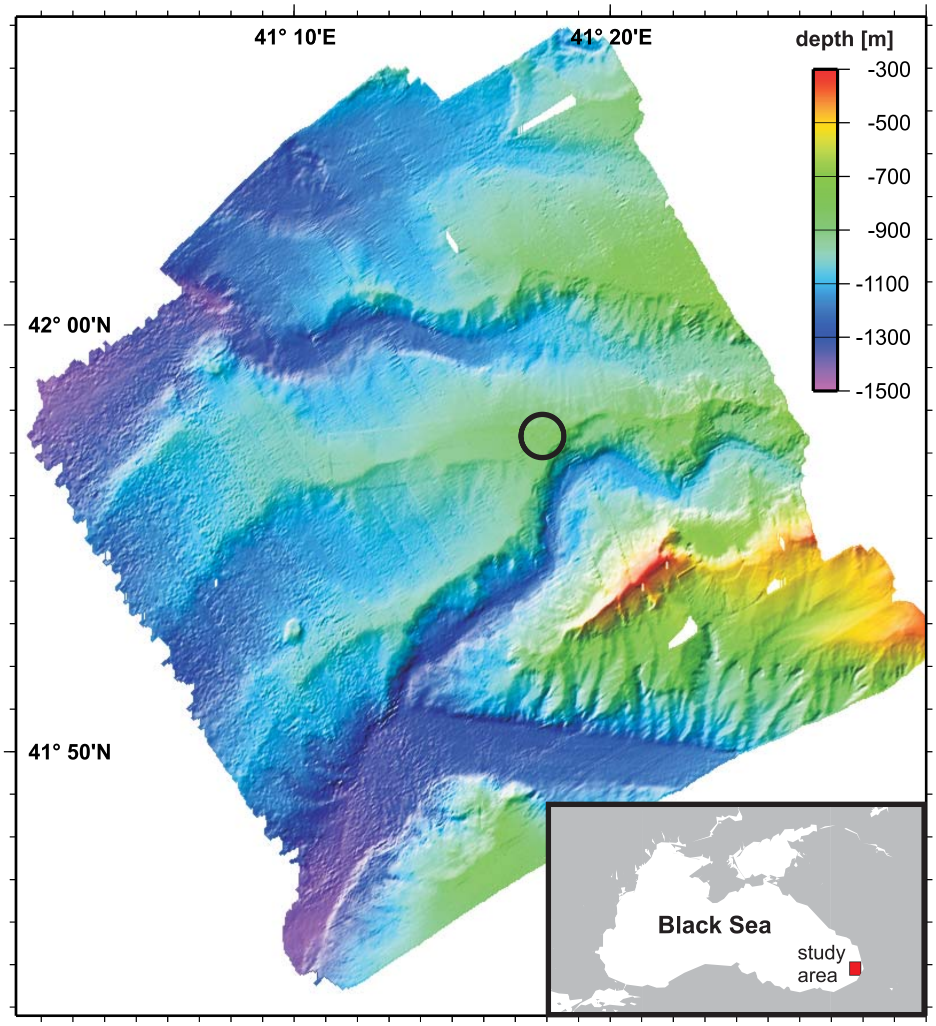

Fig. 2. Bathymetric grid of the area offshore Georgia studied during the METRO project. Data have been acquired with a portable ELAC Bottomchart Mk.II (Mark II) multibeam system working at 50 kHz. Grid cell size is 50 meters. Circle shows the location of seeps shown in Figure 1.

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Modeling Past Atmospheric CO_2: Results of a Challenge

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The models and concepts used to predict future climate are based on physical laws and information obtained from observations of the past. New paleoclimate records are crucial for a test of our current understanding.

The Vostok ice core record [*Petit et al.*, 1999] showed that over the past 420 kyr (1 kyr = 1000 years), Antarctic climate and concentrations of the greenhouse gases carbon dioxide (CO_2) and methane (CH_4) were tightly coupled. In particular, CO_2 seemed to be confined between bounds of about 180 ppmv (parts per million by volume) in glacial periods and 280 ppmv in interglacials; both gases rose and fell with climate as the Earth passed through four glacial/interglacial cycles.

During 2004, new Antarctic temperature and dust records from the European Programme for Ice Coring in Antarctica (EPICA) Dome C (EDC) ice core were published extending back to 740 kyr [*EPICA Community Members*, 2004]. The early part of the record shows a changed behavior, with much weaker but longer interglacials. The imminent appearance of an ice core record of atmospheric CO_2 covering the same period prompted a challenge issued in an *Eos* article at the end of last year [*Wolff et al.*, 2004] for the modeling community to predict, based on current knowledge, what the greenhouse gas records will look like.

This article describes the submissions to the challenge. Several groups took up this "EPICA challenge," using models, concepts, and correlations; their predictions were presented as posters at the 2004 AGU Fall Meeting.

Although different approaches were used, most of the teams effectively assume that Southern Ocean processes are the main control on atmospheric CO_2. Most of them expect that the CO_2 concentration will look very similar to Antarctic temperature throughout the extended time period, with no overall

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trend in concentration. This means that they make a prediction that will be tested when the measured data are published: that interglacials in the pre-Vostok period, which were cooler than recent interglacials, will also have a CO_2 concentration substantially below 280 ppmv.

Eight teams sent detailed results and agreed that they could be presented together in this article (Figure 1). Two of the teams (Monnin and Joos) are in one of the laboratories that is making the CO_2 analysis of the EDC ice. However, the approaches presented here are independent of any new data, and they use only published data from other sources. For reasons of brevity, only the first author of each group has been listed.

Also, the focus is on the amplitude and frequency of changes in CO_2 concentration, rather than on the exact phasing in time: timing mismatches between entries may arise from response times in the Earth system, but may also arise from uncertainties in the timescales of the paleodata underlying some of the entries.

No group made a proposition about the past evolution of CH_4 prior to 420 kyr (the Vostok period). The entries for CO_2 range from simple correlations using existing paleodata through to complete biogeochemical carbon cycle models. Each entry can be seen as testing a particular hypothesis, whose validity may be judged when the extended data set from EDC is published.

Correlations with Ice Core Data

Two entries involve a correlation with ice core data only, using Vostok, or the shallow part of EDC, as a training set. The first of these (Mudelsee) finds the best linear relationship between CO_2 from Vostok and deuterium (the temperature proxy) from EDC to 414 kyr, allowing a small time lag [*Mudelsee*, 2001]. The entry then extends the record to 740 kyr using deuterium from EDC. This predicts that CO_2 minima in the earlier period are around 200 ppmv, with maxima around 250–260 ppmv, significantly lower than during the Vostok era. This prediction can be seen as a test of whether Antarctic (and, by implication, Southern Ocean) temperature is the major control on global atmospheric CO_2 content.

Monnin's entry relates CO_2 concentration to EDC data for deuterium (linear) and dust concentration (logarithmic) for only the last 22 kyr [*Monnin et al.*, 2001] and extends the relationship between CO_2 and these variables back in time. Given the limited calibration period, this leads to a surprisingly good correlation with existing Vostok CO_2 data. Monnin's entry predicts minima in the pre-Vostok era (420–740 kyr) similar to those afterward (180–200 ppmv), with maxima of only 250–260 ppmv (compare 280–300 ppmv in the Vostok era). The underlying assumption is that the CO_2 concentration is controlled by Southern Ocean factors such as sea ice extent and sea surface temperature (with deuterium as their proxy) and iron supply (with dust as its proxy).

Correlations with Marine Sediment Data

Two entries involve a correlation with marine sediment data. One of them (Shackleton) uses only the benthic oxygen isotope record, after subtracting the part that appears to be linearly related (with appropriate time lags) to orbital forcing [*Shackleton*, 2000]. The entry is based on a hypothesis that CO_2 is the key player in transmitting and amplifying the ice age cycles, and that it ultimately plays a large role in controlling factors such as deepwater temperature and ice volume (which are recorded in the benthic record). Thus, CO_2 can be inverted from the benthic data. This method also gives a surprisingly good agreement with Vostok CO_2 and, in common with many other entries, suggests pre-Vostok interglacial values of around 250–260 ppmv.

Flower's entry, which also involves a correlation with marine sediment data, supposes that chemical stratification and associated carbonate compensation is an important means of sequestering CO_2 in the deep ocean [*Flower et al.*, 2000] and that it therefore controls atmospheric CO_2. The gradient of the carbon isotopic composition ($\delta^{13}C$) between intermediate and deep waters in the Atlantic is used, with

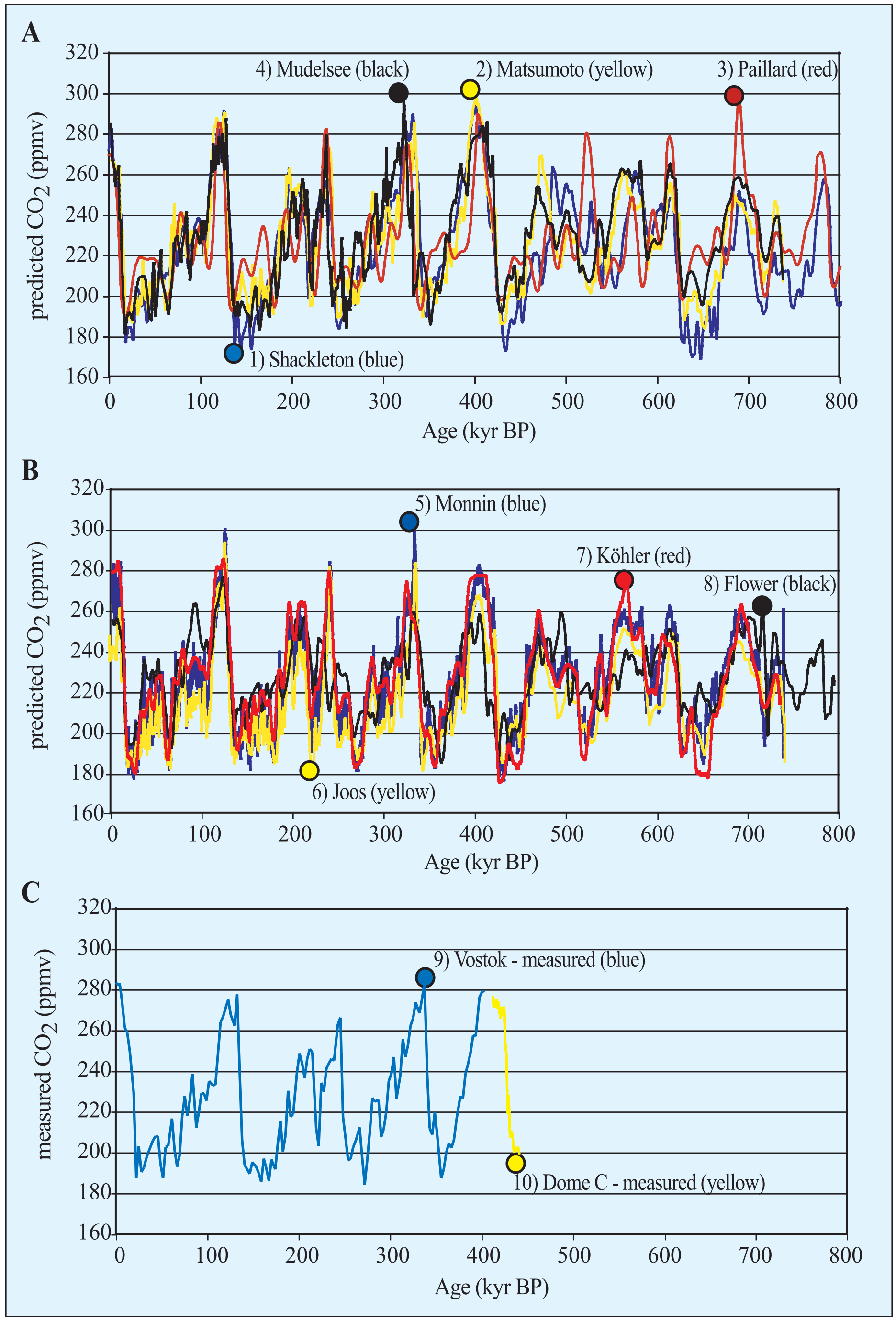

Fig. 1. (a and b) Predictions of CO_2 concentration over the past 740 kyr, labeled with the name of the respective lead author. (c) CO_2 concentrations measured in ice cores. The Vostok data are on the timescale known as GT4 [Petit et al., *1999*]*; the small amount of additional data published so far from the EPICA Dome C core (EDC2 timescale) are included* [EPICA Community Members, *2004*]*. The two timescales have a small mismatch at the period of overlap between the two records, but this presentation allows the changes in CO_2 occurring at the glacial/interglacial transition known as Termination V, about 430 kyr B.P., to be seen.*

the constant of proportionality between CO_2 and this gradient determined from Vostok data. In this entry, the prediction has a different pattern: pre-Vostok minima around 200–210 ppmv and maxima around 250–260 ppmv. Although the maxima numbers are low, they are similar to this model's prediction for each interglacial prior to the last one.

Other Approaches

One entry (Joos) looks at the problem from a different perspective. It assumes that irrespective of the cause of CO_2 variations, low-frequency variations in Antarctic temperature (represented by deuterium) are determined by radiative forcing from three main components: CO_2, aerosol (represented by ice core dust), and ice sheet extent (represented by marine benthic oxygen isotope content ($\delta^{18}O$)). The equations can be inverted to determine the CO_2 concentration. Parameters for the strength of forcing from each factor are chosen to match the Vostok record. In practice, this uses correlations similar to some of the other entries and finds reduced interglacial values (240–250 ppmv) in the pre-Vostok era.

This entry demonstrates the difficulty of separating out cause and effect in simple correlative approaches, because Antarctic temperature forces CO_2 change in several entries, and CO_2 forces temperature in this entry; Antarctic dust acts as a proxy for aerosol forcing of Antarctic temperature (Joos) and as a proxy for iron-fertilization-induced CO_2 changes (Monnin).

One entry uses even more inputs in a multiple linear regression model (Matsumoto): Vostok CO_2 data are fitted to a combination of Vostok deuterium and dust, paleoceanographic proxies for deep ocean carbonate dissolution, North Atlantic deepwater formation and ice volume, and calculated insolation at various latitudes. Using the EDC deuterium and dust data in place of the equivalent Vostok data, this model predicts reduced pre-Vostok interglacial CO_2 concentrations, in common with many of the other models. In practice, the ice core deuterium record explains much of the variance in the CO_2 record in the multiple linear regression model.

Another entry (Köhler) uses an ocean-atmosphere-biosphere box model [*Köhler et al.*, 2005] of the carbon cycle (including isotopes of carbon), in which many of the important processes are physically parameterized. The model is forced by ice core and marine data sets, and it represents the most complete attempt in this exercise. This model predicts higher CO_2 values than many of the entries in pre-Vostok interglacials (up to 270 ppmv in marine isotope stage 15). It does a reasonable job of simulating Vostok data, and it has the advantage that ice core and marine $\delta^{13}C$ data can be used as additional constraints on the outcome. On the basis of this modeling exercise, deep stratification of the Southern Ocean, changes in sedimentation/dissolution rates of calcium carbonate, and iron fertilization all contribute significantly to the glacial/interglacial CO_2 cycles.

Finally, one entry (Paillard) uses a conceptual model that predicts global ice volume and CO_2 using only the insolation forcing as input and a set of threshold rules [*Paillard and Parrenin*, 2004]. The hypothesis is that deglaciations are triggered by glacial maxima, through a mechanism that involves atmospheric CO_2. When the Antarctic ice sheet reaches its maximum extent, deep ocean stratification breaks down, leading to a rapid increase in atmospheric CO_2. In contrast to most of the other entries, this model predicts no significant difference between the pre-Vostok and Vostok eras.

In summary, most entrants predict lower CO_2 concentrations in pre-Vostok interglacials, in line with lower Antarctic temperatures. No entry expects any overall trend in CO_2 concentration to be seen. Most of them implicitly assume that processes in the Southern Ocean control changes in atmospheric CO_2 and that CO_2 and Antarctic temperature will remain very tightly coupled through the entire period.

When the CO_2 data from the EPICA ice core itself appear, they will show if these simple conclusions in these models are confirmed. The similar results from different approaches used here might appear surprising, but this should not be interpreted as meaning that there is a good common understanding of the dynamics of past changes in atmospheric CO_2. Because most of the entries used a correlative approach, and all used other paleoclimatic time series, the comparison with the data will address only the more limited question of whether we have an understanding of the relationship between CO_2 and other aspects of climate.

The similar results reflect the fact that most climate variables respond together at major glacial/interglacial transitions. Between transitions, different processes sometimes act in isolation, and differences in detail of the model outputs should be helpful in assessing the importance of each process. The timing of change may also be diagnostic; this will require increased certainty in the synchronization of timescales between ice core gas records, ice core climate records, marine records, and absolute age (determining orbital changes).

The EDC CO_2 and CH_4 records back to 650 kyr are expected to be published during 2005. They are likely to become new iconic curves, and targets for all who wish to understand the Earth system well enough to predict its future evolution.

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