

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 geoaoustic mapping of the cold seep sites in order to derive better regional methane flux estimates.

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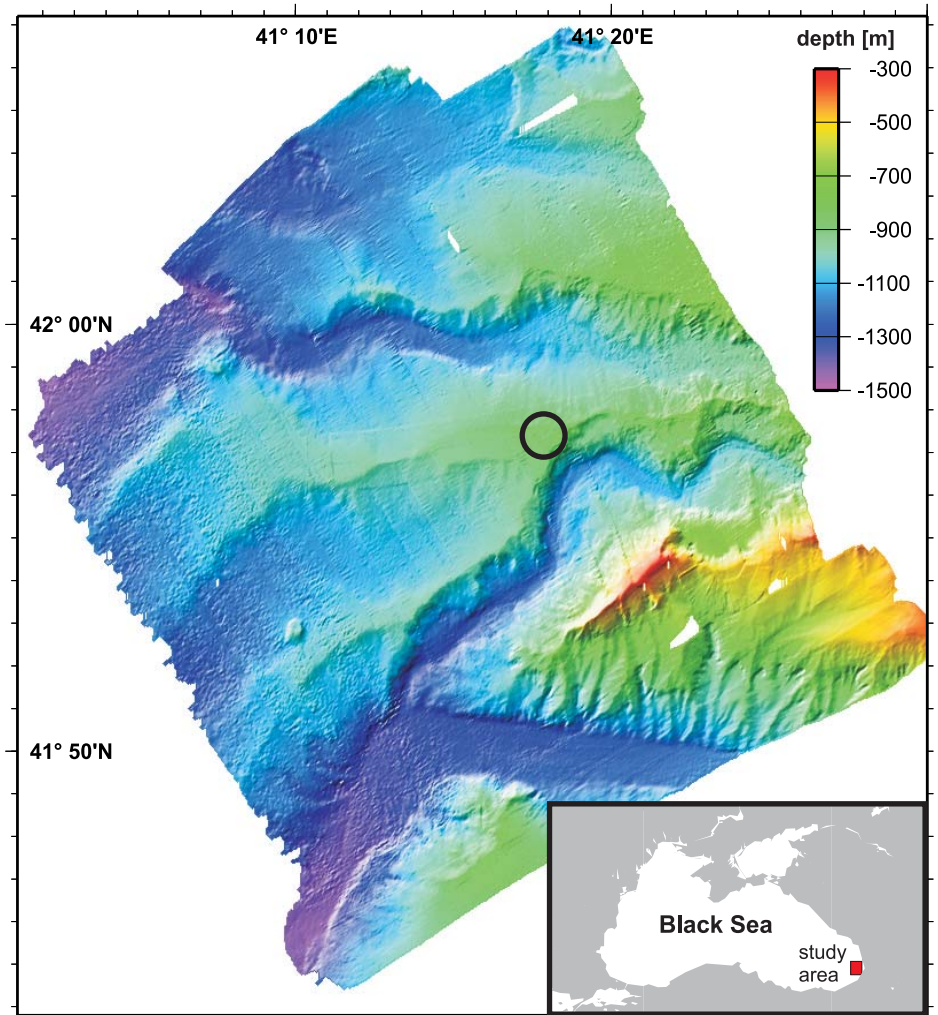


Fig. 2. Bathymetric grid of the area offshore Georgia studied during the METRO project. Data have been acquired with a portable ELAC Bottomchart Mr.II (Mark II) multibeam system working at 50 kHz. Grid cell size is 50 meters. Circle shows the location of seeps shown in Figure 1.

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## Modeling Past Atmospheric CO<sub>2</sub>: 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

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years), Antarctic climate and concentrations of the greenhouse gases carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) were tightly coupled. In particular, CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>. Most of them expect that the CO<sub>2</sub> concentration will look very similar to Antarctic temperature throughout the extended time period, with no overall



the constant of proportionality between CO<sub>2</sub> 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<sub>2</sub> variations, low-frequency variations in Antarctic temperature (represented by deuterium) are determined by radiative forcing from three main components: CO<sub>2</sub>, aerosol (represented by ice core dust), and ice sheet extent (represented by marine benthic oxygen isotope content (δ<sup>18</sup>O)). The equations can be inverted to determine the CO<sub>2</sub> 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<sub>2</sub> change in several entries, and CO<sub>2</sub> 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<sub>2</sub> changes (Monnin).

One entry uses even more inputs in a multiple linear regression model (Matsumoto): Vostok CO<sub>2</sub> 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<sub>2</sub> concentrations, in common with many of the other models. In practice, the ice core deuterium record explains much of the variance in the CO<sub>2</sub> 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<sub>2</sub> 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 δ<sup>13</sup>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<sub>2</sub> cycles.

Finally, one entry (Paillard) uses a conceptual model that predicts global ice volume and CO<sub>2</sub> 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<sub>2</sub>. When the Antarctic ice sheet reaches its maximum extent, deep ocean stratification breaks down, leading to a rapid increase in atmospheric CO<sub>2</sub>. 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<sub>2</sub> concentrations in pre-Vostok interglacials, in line with lower Antarctic temperatures. No entry expects any overall trend in CO<sub>2</sub> concentration to be seen. Most of them implicitly assume that processes in the Southern Ocean control changes in atmospheric CO<sub>2</sub> and that CO<sub>2</sub> and Antarctic temperature will remain very tightly coupled through the entire period.

When the CO<sub>2</sub> 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<sub>2</sub>. 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<sub>2</sub> 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<sub>2</sub> and CH<sub>4</sub> 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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