THE EPICA CHALLENGE (1)

predicting CO_2 over 800,000 years

Christoph Kull[1], Jerome Chappellaz[2], Hubertus Fischer[3], Heinz Miller[4], Thomas F. Stocker[5], Andrew J. Watson[6] and Eric W. Wolff[7]

[1]PAGES International Project Office, Bern, Switzerland; [2]Laboratoire de Glaciologie et Géophysique de l'Environnement, Grenoble, France
[3,4]Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; [5]Physics Institute, University of Bern, Switzerland
[6]University of East Anglia, Norwich, UK; [7]British Antarctic Survey, Cambridge, UK

The Vostok ice core showed that, over the last 420 kyr, Antarctic climate and concentrations of greenhouse gases (CO_2 and CH_4) were tightly coupled. In particular, CO_2 seemed to be confined between bounds of about 180 ppmv in glacial periods to 280 ppmv in interglacials. The Vostok data are telling us how the coupled Earth system behaves – now we have to understand why it behaves this way. During 2004, The European Project for Ice Coring in Antarctica (EPICA) published new Antarctic temperature and dust records extending back to 740 kyr. The early part of the record shows a changed behaviour, with much weaker but longer interglacials. Greenhouse gas data for this extended period will soon be available, and obvious questions arise: Will CO_2 retain its interglacial bound in weak interglacials or will a new upper bound be seen? Is there any trend in average CO_2 over 800 kyr?
This provides an unusual opportunity for modellers and others to predict what the data will look like in advance and to allow us to explore the underlying assumptions behind ideas and models. Several groups took up this "EPICA challenge", using models, concepts and correlations. In these posters we summarise their predictions. There is no prize and we will not be declaring a winner. But we hope that the results will lead to a greater understanding and better models.

The EPICA Challenge: Inversion of CO_2 radiative forcing from the deuterium temperature proxy record

F. Joos and E. Monnin, Climate and Environmental Physics, Physics Institute
University of Bern, Switzerland; joos@climate.unibe.ch

We judge it as elusory to attempt for a mechanistic carbon cycle-biogeochemical modelling explanation in face of the difficulties to explain the CO_2 rise during the well-documented last transition. Instead, we utilize the climate sensitivity concept to link radiative forcing and temperature. The idea is that the EPICA δD record reflects the temperature in Antarctica caused by radiative forcing from CO_2 and other components. The δD record is inverted for atmospheric CO_2 taking into account the estimated influence of radiative forcing by ice sheets and atmospheric aerosols.

The following relationship is applied to obtain a normalized CO_2 record from a normalized δD record:

$$CO_{2,N}(t) = \frac{1}{1-\alpha_{ice}-\alpha_{dust}} \cdot \left(\delta D_N(t) - \alpha_{ice} \cdot RF_{ice,N} - \alpha_{dust} \cdot RF_{dust,N}\right) \quad (1)$$

α_{ice} and α_{dust} are the fraction of ice and dust forcing of the total radiative forcing by ice and dust and CO_2.

Normalized radiative forcings by ice sheets, $RF_{ice,N}$, and by aerosols, $RF_{dust,N}$, relative to interglacial conditions are estimated from the benthic $\delta^{18}O$ record, a proxy for ice volume, and the EPICA dust record, a proxy for atmospheric aerosol loading assuming logistic relationships. The proxy records have been normalized (δD_N $\delta^{18}O_N$, $dust_N$) between 0, for typical interglacial levels, and –1, for glacial values. Then, we obtain for atmospheric CO_2:

$$CO_2(t) = CO_{2,IG} + (CO_{2,IG} - CO_{2,G}) \cdot \frac{1}{1-\alpha_{ice}-\alpha_{dust}} \cdot \left(\delta D_N(t) - \alpha_{ice} \cdot (-1+K_{ice}) \cdot \frac{\delta^{18}O_N(t)}{\delta^{18}O_N(t)+K_{ice}} - \alpha_{dust} \cdot (-1+K_{dust}) \cdot \frac{dust_N(t)}{dust_N(t)+K_{dust}}\right) \quad (2)$$

An example solution is given in Figure 1.

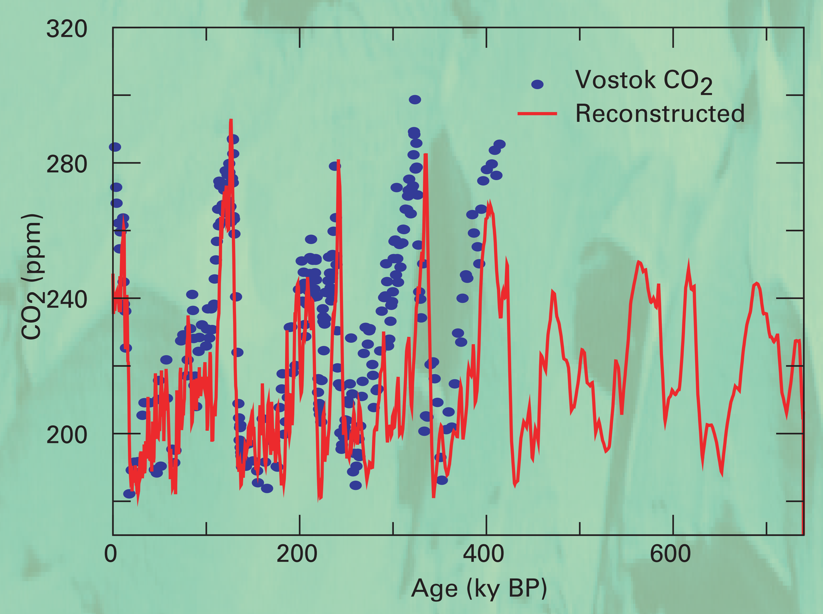
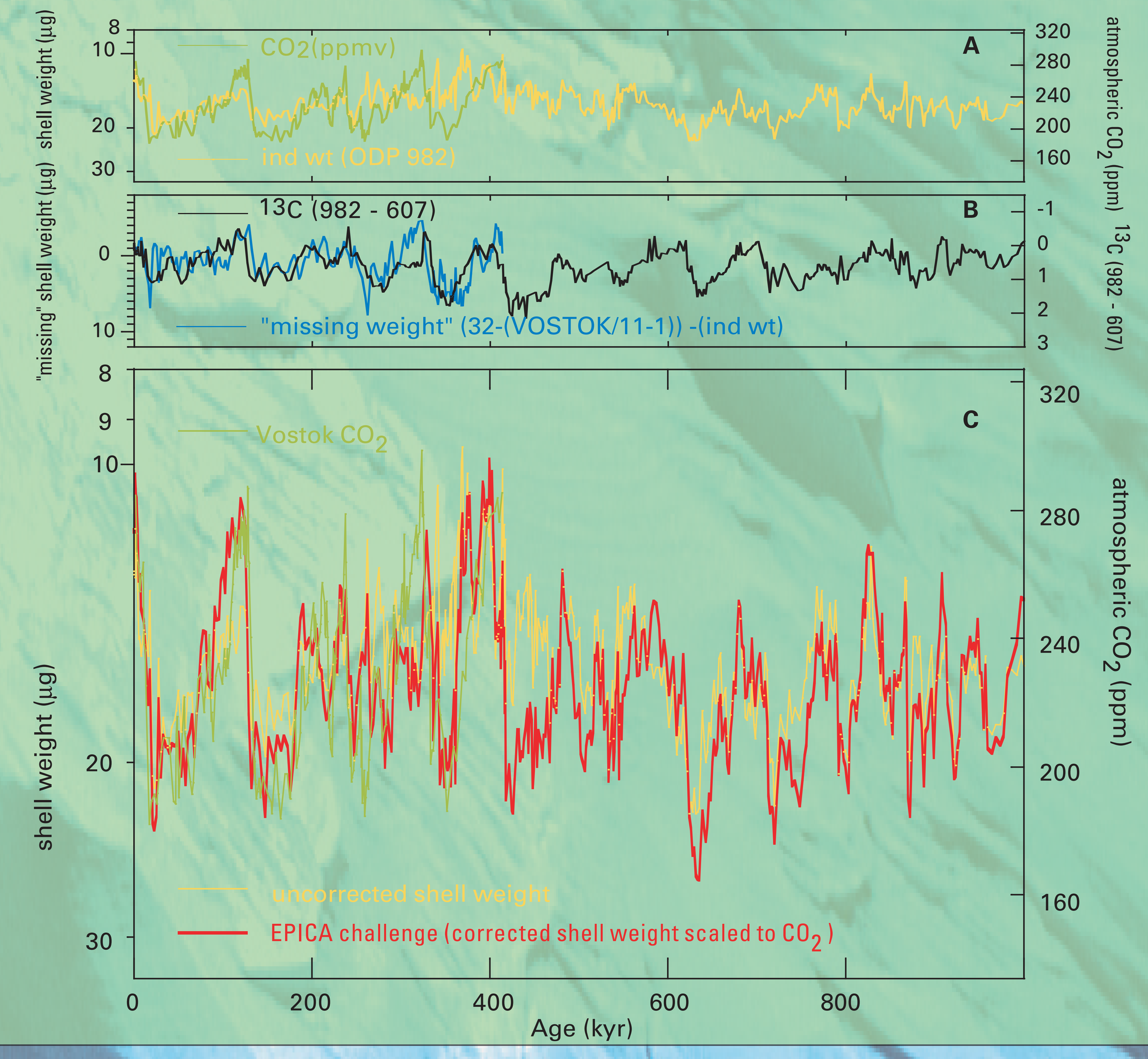


Figure 1: A comparison between the reconstructed CO_2 values (red) and the Vostok ice core record (blue). Atmospheric CO_2 has been reconstructed from equation (2) using the EPICA δD and dust record (EPICA community members, Nature, 2004) and the benthic $\delta^{18}O$ record from Karner et al., Paleoceanography, 2002. The parameter values used are α_{ice}=0.3, K_{ice}=--0.15, α_{dust}=0.05; K_{dust}=-0.2. The interglacial and glacial values used for the normalization of the proxy records are 269 ($CO_{2,IG}$) and 185 ppm ($CO_{2,G}$) for CO_2, -368 and –444 permil for δD, -0.9 and +0.65 permil for $\delta^{18}O$, and 0 and 1400 microgram per litre meltwater for dust.

EPICA CO_2 prediction using "dissolution corrected" foraminiferal shell weights

S. Barker and H. Elderfield, Lamont-Doherty Earth Observatory of Columbia University, USA; sbarker@ldeo.columbia.edu

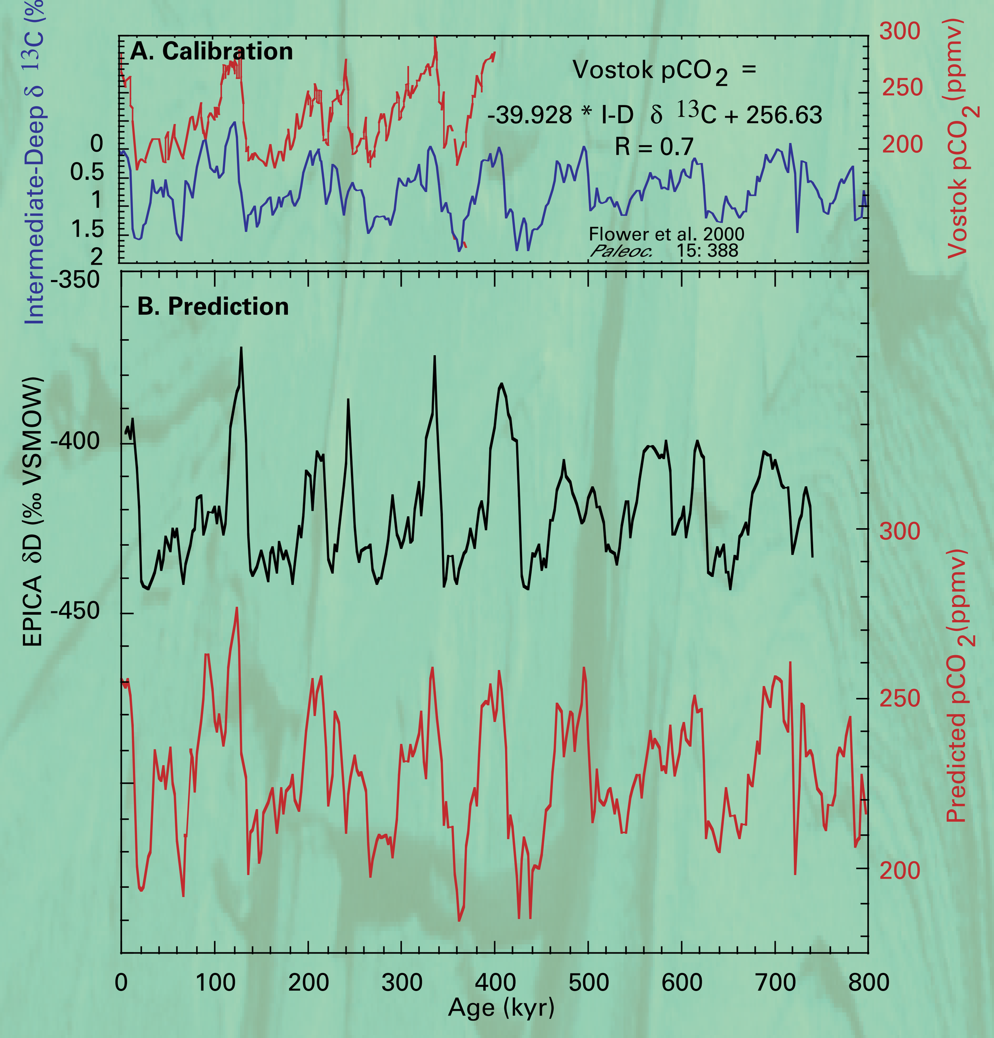
Working on the premise that the shell weights of planktonic foraminifera reflect the carbonate chemistry of surface waters and therefore respond to changes in atmospheric CO_2 (Barker and Elderfield, 2002) a 1Myr shell weight record for *G. bulloides* was produced from core ODP 982 in the North Atlantic (57.5°N, 15.9°W, 1134m). Despite its shallow depth, we discovered that the core appeared to have been subject to dissolution during the Mid-Brunhes (Fig. A) and as such needs to be corrected for shell weight loss at the seafloor. Correction has been made using a correlation between the hypothetical "missing weight" (scaled Vostok minus measured weight) and the difference between benthic $\delta^{13}C$ at the sites of ODP 982 and ODP 607 in the deep North Atlantic (Fig. B) as a simple measure of foraminiferal corrosion. The resulting "corrected" shell weight record is shown in Fig. C and scaled to CO_2 from Vostok. The reconstruction takes no account of changing temperature, salinity or alkalinity, which will all affect the shape and amplitude of variability through their effect on carbonate chemistry. It also ignores other possible "vital" controls on shell weight such as salinity, nutrients etc. and assumes that our simple dissolution correction is valid. Allowing for such uncertainties, the features which best characterise our predicted pre-Vostok CO_2 are: (a) generally low interglacial CO_2 prior to MIS 11 (reminiscent of the pre-Vostok EPICA temperature record) and (b) particularly low CO_2 during glacial stage 16.



Prediction of EPICA pCO_2 by Atlantic chemical stratification

B. Flower, College of Marine Science,
University of South Florida, USA; bflower@marine.usf.edu

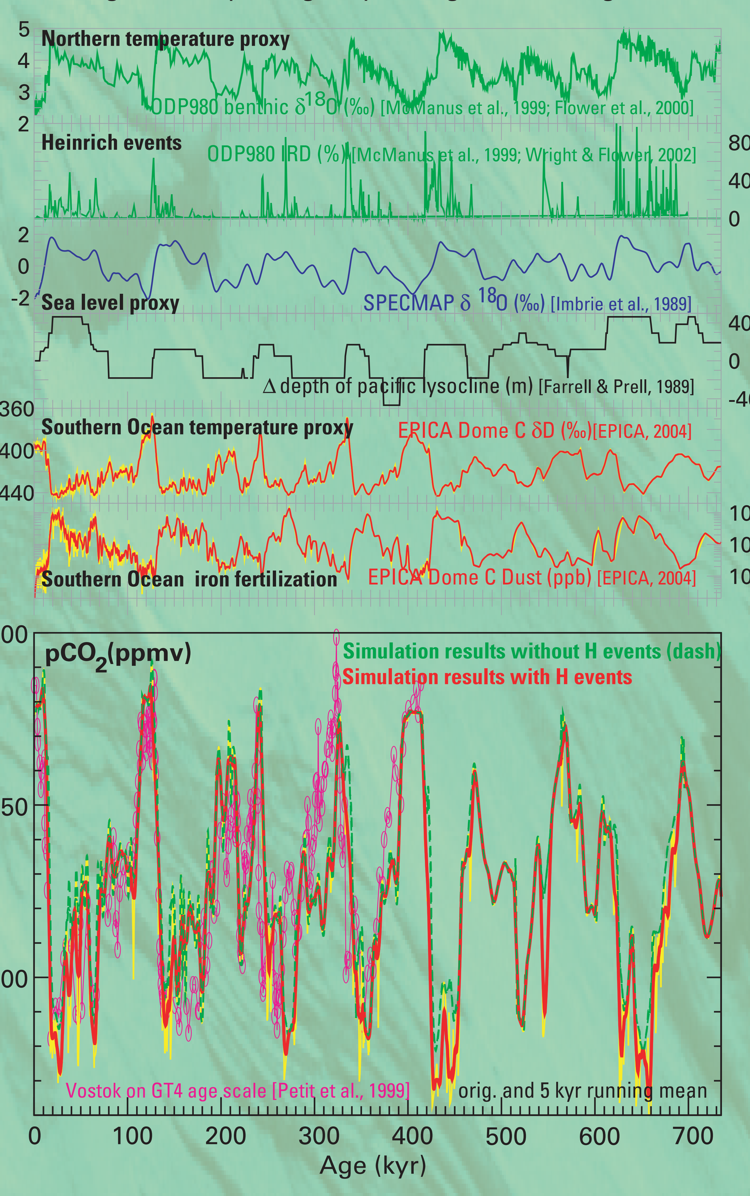
Chemical stratification and associated carbonate compensation is an important means of sequestering CO_2 in the deep ocean and has a strong relation to Vostok pCO_2 (Flower et al., 2000, Paleoceanogr., 15: 388). Here I develop an empirical calibration relating the intermediate-to-deep Atlantic $\delta^{13}C$ gradient (ODP Sites 982 - 665) to Vostok pCO_2 (panel A). I derive a predicted pCO_2 curve for the past 800 ka compared to EPICA δD of precipitation (EPICA community members, 2004, Nature, 429: 623), which is a proxy for Antarctic air temperature (panel B). The reconstruction suggests (1) a somewhat smaller range of glacial-interglacial pCO_2 (~50 ppmv) for 800-400 ka compared to 400-0 ka, (2) similar levels during interglaciations throughout the past 800 ka, and (3) higher pCO_2 levels during glaciations 800-400 ka (~210 ppmv) compared to the lowest levels from 400-0 ka. This pattern is in contrast to the EPICA δD record, which indicates cooler interglacial Antarctic air temperatures from 800-400 ka compared to subsequent interglaciations. If confirmed by actual measurements, these relationships have the interesting implication that interglacial Antarctic air temperature has become more sensitive to pCO_2 levels during the past 400 ka.



EPICA - CO_2 prediction

P. Köhler, Alfred Wegener Institute for Polar and Marine Research,
Bremerhaven, Germany; pkoehler@awi-bremerhaven.de

I used a box model (Köhler et al., 2004, submitted to GBC) to reconstruct pCO_2. Taken the same processes identified as possible causes for observed changes in pCO_2, $\delta^{13}C$ and $\Delta^{14}C$ during Termination I especially previous terminations were matched by the simulation results with good accuracy. Due to timing uncertainties of our forcing data sets (10-20 kyr) and their coarse temporal resolution (1-3 kyr) fast fluctuations are probably not matched very well. The identification of Heinrich events with reduced NADW formation on the basis of the IRD in one North Atlantic sediment core might lead to mismatches, I therefore show simulation results with and without the Heinrich events matching Vostok ice core data on their GT4 age scale with similar accuracy (r = 0.70 and r = 0.72). The main processes determining pCO_2 are exchange processes of alkalinity and DIC between ocean and sediment, changes in the vertical mixing of the water column and iron fertilization of the marine export production in the Southern Ocean followed by changes in oceanic temperature and the strength of the NADW formation. The dynamics of sea level, terrestrial biosphere and gas exchange through sea ice work in the opposite direction increasing a measured rise in pCO_2 of 80 ppmv by another 30 ppmv. Coral reef growth impacting only during sea level high stands is not considered.



PAGES IPO, Sulgeneckstrasse 38, CH 3007 Bern, Switzerland. contact: kull@pages.unibe.ch

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