Proposing a mechanistic understanding of atmospheric CO_2 during the last 740,000 years — a contribution to the EPICA challenge

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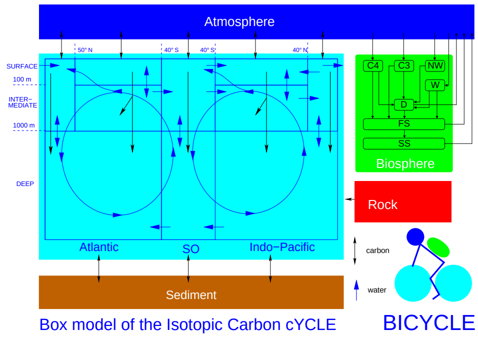
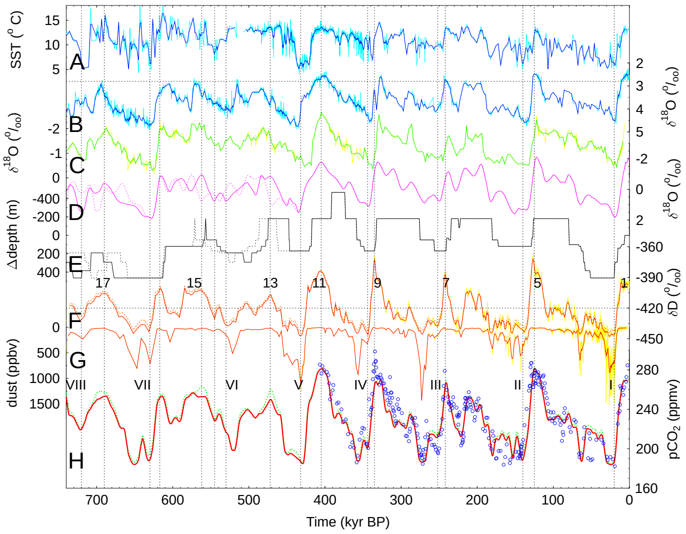
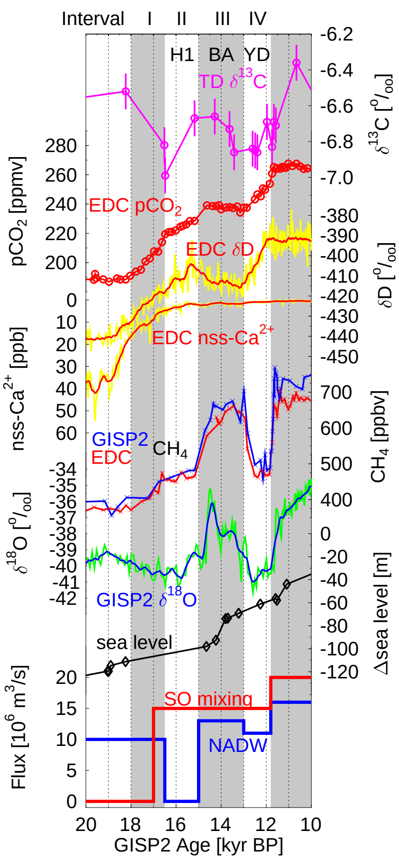
Paleo-records in Antarctic ice cores revealed strong glacial/interglacial variations in temperature, atmospheric dust as well as carbon dioxide. To date, the longest CO_2 record derived from the Vostok ice core goes back in time as far as about 410 kyrs showing that CO_2 concentrations vary between 280 and 180 ppmv for interglacials and glacials, respectively. Latest measurements of dust and isotope temperatures on the new EPICA ice core from Dome C (EDC), cover the last 740 kyrs, i.e. four more glacial cycles which showed, however, reduced temperature amplitudes compared to the Vostok time span. This new archive offers the possibility to propose atmospheric CO_2 changes for the pre-Vostok era as called for in the EPICA challenge (Wolff et al., 2004, The EPICA challenge to the Earth System Modeling Community. EOS 85: 363). Here, we contribute to this challenge using a box model of the isotopic carbon cycle based on process understanding previously derived for Termination I. Our Box model of the Isotopic Carbon cYCLE BICYCLE (Köhler et al. Quantitative interpretation of atmospheric carbon records over the last glacial termination, GBC, doi:101029/2004GB002345) consists of ten ocean resvervoir in three high layers distinguishing Atlantic, Indo-Pacific, and Southern Ocean, a seven compartment terrestrial biosphere and considers also fluxes of dissolved inorganic carbon and alkalinity between ocean and sediments. BICYCLE is forced by various ice core and marine sediment records to depict observed changes in temperature, sea level, lysocline dynamics, and aeolian iron input into the Southern Ocean. Our results show that major features of the Vostok period are reproduced while prior to Vostok our model predicts significantly smaller amplitudes in CO_2 variations. The contributions in decreasing order to the rise in pCO_2 were given by changes in exchange fluxes between ocean and sediment (on average 46 ppmv during Termination V to I and 27 ppmv earlier), SO vertical mixing (42/25 ppmv), iron fertilisation (26/18 ppmv), SST (25/13 ppmv), and NADW formation (12/2 ppmv). Changes in sea level (−8/−4 ppmv), sea ice cover (−6/−6 ppmv), and terrestrial carbon storage (−24/−12 ppmv) were processes enlarging the observed pCO_2 rise by up to 50 ppmv during terminations. While most processes were reduced in their magnitude prior to Termination V, the absolute contribution of iron fertilisation changed only slightly. Thus, the relative importance of biogeochemical processes is enhanced from 45% to 60% during these early terminations. The contribution of physical processes (SST, sea level, sea ice) to the pCO_2 rise during terminations stayed always below 20%, while ocean circulation contributed on average 50% during the Vostok period (including Termination V), but only 30–40% during Termination VI and VII.

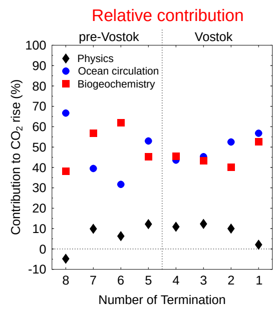


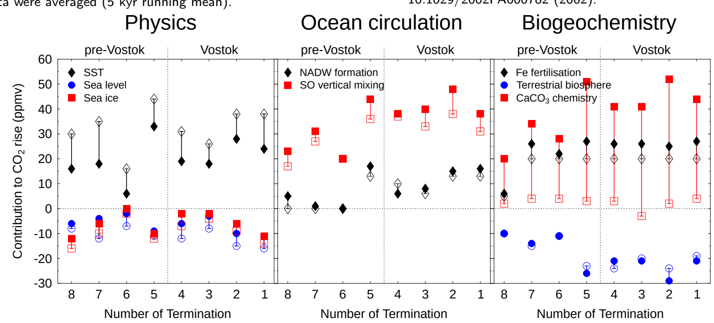


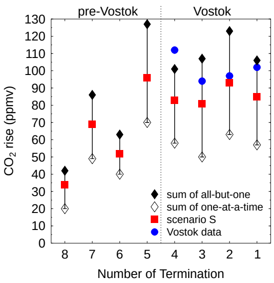
The EPICA challenge (Köhler and Fischer, submitted to Nature): Records used to force the BICYCLE model (A-G), measured and simulated pCO_2 (H). SST reconstructions (A), and (B) benthic d18O from core ODP980 (N Atlantic). C: Planktonic d18O of ODP677. D: Stacked benthic d18O of SPECMAP. E: Changes in the depth of the Pacific lysocline. Records in D and E are plotted both originally (dash) and after wiggle-matched age correction (solid). Deuterium δD (F, dash: original; solid: sea level corrected) and atmospheric dust contents (G) as measured in the EDC ice core. H: Measured Vostok pCO_2 (circles) plotted on the orbitally tuned age scale and simulated pCO_2 with (red) and without (green) age correction of SPECMAP and lysocline data. Most forcing data were averaged (5 kyr running mean).

Data references: EPICA. Nature 429, 623–628 (2004). Fairbanks. Paleoc. 5, 937–948 (1990). Farrell, Prell. Paleoc. 4, 447–466 (1989). Flower et al. Paleoc. 15, 388–403 (2000). Grootes, Stuiver. JGR 102, 26455–26470 (1997). Hughen et al. Science 303, 202–207 (2004). Imbrie et al. In: Berger et al. (eds.) 121–164 (1989). Jouzel et al. GRL 28, 3199–3202 (2001). McManus et al. Science 283, 971–975 (1999). Monnin et al. Science 291, 112–114 (2001). Petit et al. Nature 399, 429–436 (1999). Röthlisberger et al. GRL 29, 1963, 10.1029/GL015186 (2002). Shackleton. Science 289, 1897–1902 (2000). Shackleton, et al. Trans. Royal Soc. Edinburgh: Earth Sc. 81, 251–261 (1990). Smith et al. Nature 400, 248–250 (1999). Stuiver et al. Radiocarbon 40, 1041–1083 (1998). Wright, Flower. Paleoc. 17, 1068, doi: 10.1029/2002PA000782 (2002).









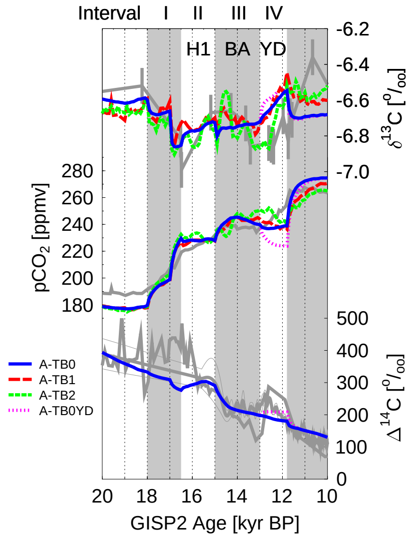
Results of the EPICA challenge:

Top left: Relative contribution of processes detailing with physics, ocean circulation, and biogeochemistry to the rise in CO_2 during the last eight glacial terminations. These are sum-ups from results of all-but-one process forced at a time of individual analysis (see top right).

Top right: Contribution of each process to CO_2 rise. Considered here were changes in sea surface temperature (SST), sea lvel, gas exchange through sea ice coverage, NADW formation, Souther Ocean (SO) verticla mixing, iron (Fe) fertilisation, terrestrial carbon storage, and dissolution/sedimentation of $CaCO_3$. Forcing the model with either one process at a time (open symbols) or with all but one process at a time (closed symbols).

Left: Sum of individual processes (all-but-one, one-at-a-time,) results of standard scenario S, and Vostok data.

Acknowledgements: The EPICA challenge team for the inspiring scientific quest.



Termination I (Köhler et al., GBC): Top: Forcings of BICYCLE. Bottom: Simulated and measured atmospheric CO_2, $\delta^{13}C$, $\Delta^{14}C$.

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