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

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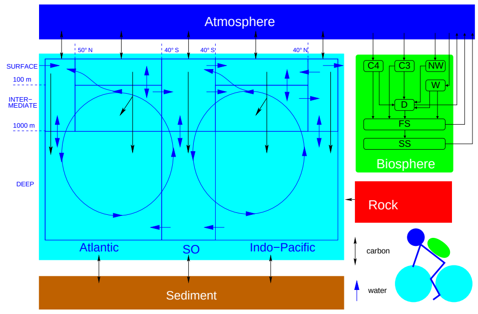
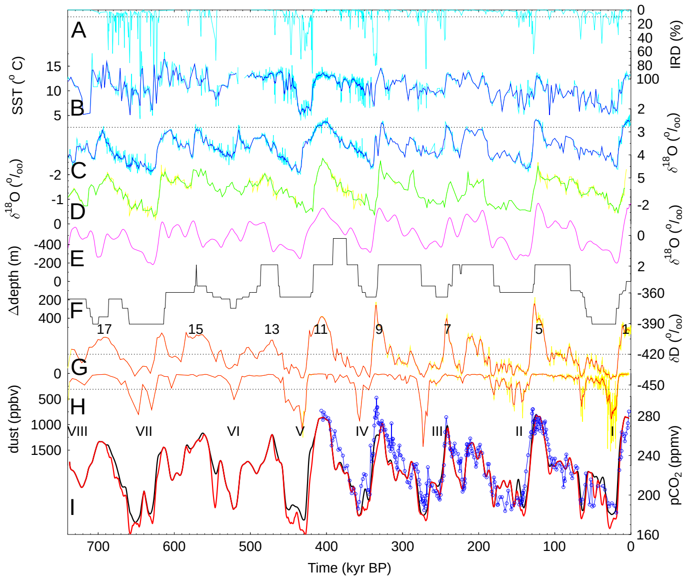
Paleo-records in Antarctic ice cores revealed strong glacial/interglacial variations in temperature, atmospheric dust as well as carbon dioxide. To date, the longest CO_2 record derived from the Vostok ice core goes back in time as far as about 410 kyrs showing that CO_2 concentrations vary between 280 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, submitted to GBC.) 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 main contributions (in decreasing order) to the variations in pCO_2 were given by changes in Southern Ocean vertical mixing, exchange fluxes between ocean and sediment, sea surface temperature, North Atlantic deep water formation, iron fertilisation, and Heinrich events. While most processes were reduced in their magnitude during the terminations of the pre-Vostok period, the absolute contribution of iron fertilisation changed only slightly. Thus, the relative importance of biological and biogeochemical processes is enhanced (approx. doubling their relative share) in the pre-Vostok period. The contribution of physical processes (ocean temperature, sea level, sea ice) to the pCO_2 rise during terminations stayed always below 25%, while ocean circulation contributed up to 75% during the Vostok era but less than 50% before.



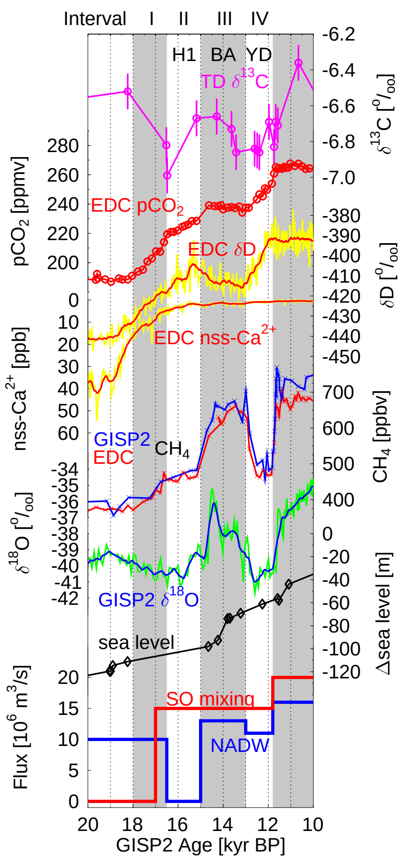
Box model of the Isotopic Carbon cYCLE **BICYCLE**

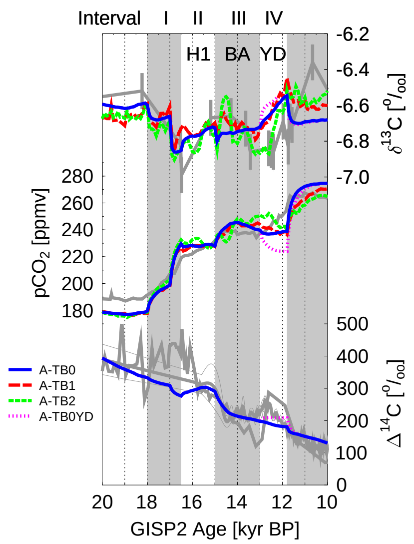


The EPICA challenge (Köhler and Fischer, submitted to Nature): Records used to force the BICYCLE model (A-H), measured and simulated pCO_2 (I). SST reconstructions (A), IRD (B) and benthic $\delta^{18}O$ from core ODP980 (N Atlantic). D: Planktonic $\delta^{18}O$ of ODP677. E: Stacked benthic $\delta^{18}O$ of SPECMAP. F: Changes in the depth of the Pacific lysocline. Deuterium δD (G) and atmospheric dust contents (H) as measured in the EDC ice core. I: Measured Vostok pCO_2 (circles) plotted on the orbitally tuned age scale and simulated pCO_2 with (S, red) and without (S-H, black) a shut-down of the THC during Heinrich events.

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).

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





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

Impact of different processes on G/IG changes in pCO_2 during the last eight terminations.

Process	Impact on pCO_2 (ppmv) (one process at a time/all but one processes) I	II	III	IV	V	VI	VII	VIII
Physical processes								
SST	36/27	37/31	24/22	30/20	35/26	11/2	34/24	29/13
Sea level	–16/–9	–15/–11	–7/–4	–12/–7	–7/–5	–5/–1	–12/–8	7/5
Sea ice	–11/–5	–9/–5	–4/–2	–7/–2	–11/–3	–2/–1	–10/–6	–16/–12
Ocean circulation								
THC	13/27	13/22	6/21	10/11	13/49	0/3	0/10	0/2
Heinrich events	7/10	6/7	4/8	11/1	11/32	0/0	7/9	0/0
SO vertical mixing	30/37	28/38	23/41	30/38	14/26	14/11	23/29	15/19
Biology and biogeochemistry								
Fluxes ocean sediment	4/31	3/34	1/23	3/31	3/31	1/15	2/25	–2/7
Fe fertilisation	19/16	19/22	4/5	19/16	8/5	19/22	19/25	5/6
Terrestrial biosphere	–5(–20)/–7	–8(–22)/–10	–5(–17)/–6	–7(–24)/–7	–4/–5	–2/–4	–4/–8	–3/–2
(in brackets forced with Vostok pCO_2)								
Sum	90/127	87/128	52/108	87/101	75/156	36/41	59/100	35/38
Simulated (scenario S)	104	102	70	94	100	48	77	46
Vostok	102	97	84	112	–	–	–	–

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SPONSORED BY THE
Federal Ministry of Education and Research