Understanding the rapid rise in atmospheric CO_2 at the onset of the Bølling/Allerød

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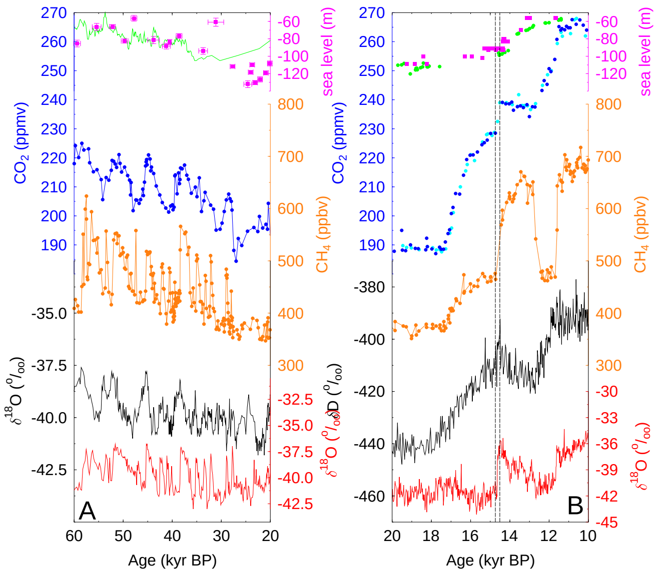
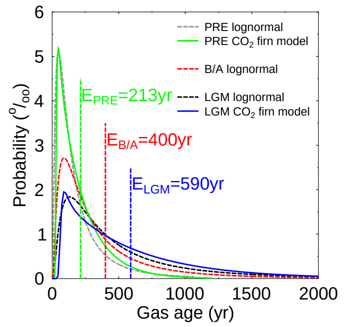
During the last glacial/interglacial transition the Earth's climate underwent around 14.6 kyr ago rapid changes. Temperature proxies from ice cores revealed the onset of the Bølling/Allerød (B/A) warm period in the north (Steffensen et al. 2008) and the start of the Antarctic Cold Reversal in the south (Stenni et al. 2001). Furthermore, the B/A is accompanied by a rapid sea level rise of about 20 m during meltwater pulse (MWP) 1A (Peltier & G.Fairbanks 2007), whose exact timing is matter of current debate (Hanebuth et al. 2000; Kienast et al. 2003; Stanford et al. 2006; Deschamps et al. 2009). *In situ* measured CO_2 in the EPICA Dome C (EDC) ice core also revealed at the same time a remarkable jump of 10 ± 1 ppmv in 230 years (Monnin et al. 2001; Lourantou et al. 2010). Allowing for the age distribution of CO_2 in firn we here show, that atmospheric CO_2 rose indeed by 20–35 ppmv in less than 200 years, which is a factor of 2–3.5 larger than the CO_2 signal recorded *in situ* in the EDC. Based on the modelled fingerprint and $\delta^{13}CO_2$ measured in EDC (Lourantou et al. 2010) we infer that 125 Pg of carbon of terrestrial origin need to be released to the atmosphere to produce such a peak. Most of the carbon might have been activated as consequence of continental shelf flooding during MWP-1A. This impact of rapid sea level rise on atmospheric CO_2 distinguishes the B/A from other Dansgaard/Oeschger (D/O) events, potentially defining the point of no return during the last deglaciation.

Paleo Records during MIS 3 and Termination I

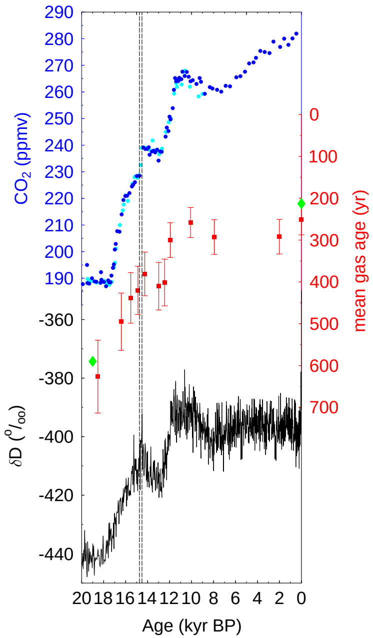


Climate records during MIS 3 and Termination I. From top to bottom: relative sea level, CO_2, CH_4 and isotopic temperature proxies (δD or δ^{18}O) from Antarctica (black) and Greenland (red). (A) MIS 3 data (Ahn & Brook 2008) from the Byrd and GISP2 ice cores. (B) Termination I data from the EDC and NGRIP ice cores (Monnin et al. 2001; Spahni et al. 2005; Stenni et al. 2001; NorthGRIP-members 2004) on the new synchronised ice core age scale (Lemieux-Dudon et al. 2010). Previous (blue) and new (cyan) EDC CO_2 data (Monnin et al. 2001; Lourantou et al. 2010). Sea level in MIS 3 from a compilation (magenta) based on coral reef terraces (Thompson & Goldstein 2007), and the synthesis (green) from the Red Sea method (Siddall et al. 2008) and for Termination I from corals (green) on Barbados, U-Th dated and uplift-corrected (Peltier & G.Fairbanks 2007), and coast line migration (magenta) on the Sunda Shelf (Hanebuth et al. 2000). Vertical lines in (B) mark the jump in CO_2 into the B/A as recorded in EDC.

Gas Age Distribution

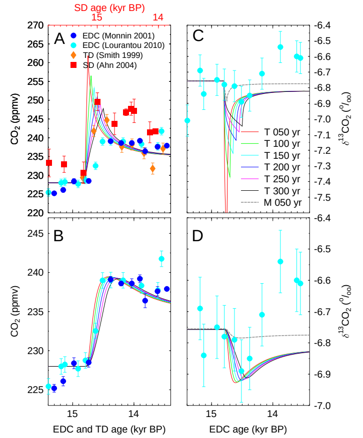


Gas age distribution as function of climate state, here pre-industrial (PRE), Bølling/Allerød (B/A) and LGM conditions. Calculation with a firn densification model (Joos & Spahni 2008) (solid lines, for PRE and LGM) and approximations of all three climate states by a lognormal function (broken).

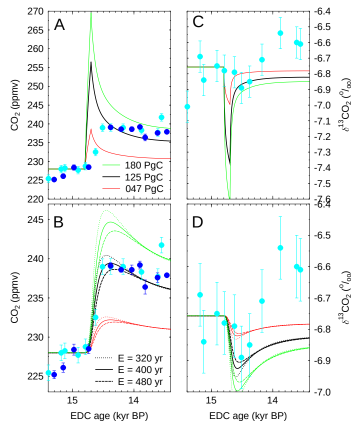


The evolution of the mean gas age ($\pm1\sigma$) during the last 20 kyr calculated with a firn densification model including heat diffusion (Goujon et al. 2003). Green diamonds represent the results for the LGM and pre-industrial climate with another firn densification model (Joos & Spahni 2008). Please note reverse y-axis. Top: EDC CO_2 (Monnin et al. 2001; Lourantou et al. 2010). Bottom: EDC δD data (Stenni et al. 2001). All records on the new age scale (Lemieux-Dudon et al. 2010).

Atmospheric CO_2 to Fullfil EDC Data

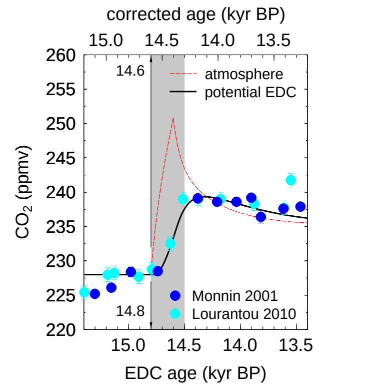


Simulations of the carbon cycle model BICYCLE for an injection of 125 PgC into the atmosphere. Injected carbon was either of terrestrial (T: $\delta^{13}C = -22.5$‰) or marine (M: $\delta^{13}C = -8.5$‰) origin. Release of C occurred between 50 and 300 years. (A) Atmospheric CO_2 from simulations and from ice cores. Siple Dome (Ahn et al. 2004) (SD, own age scale on top x-axis) and Taylor Dome (Smith et al. 1999) (TD, on revised age scale as in (Ahn et al. 2004)) . All CO_2 data synchronised to the CO_2 jump. (B) Simulated CO_2 values of (A) after the application of the gas age distribution potentially be recorded in EDC and EDC data. (C, D) Same simulations for atmospheric $\delta^{13}CO_2$, cyan dots are new EDC $\delta^{13}CO_2$ data (Lourantou et al. 2010).

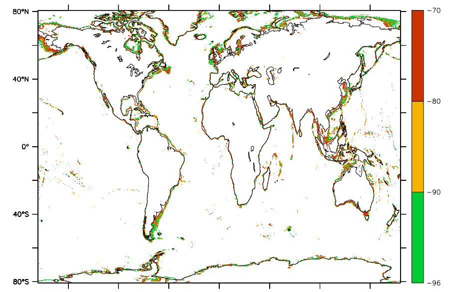


The amount of carbon (47 to 180 PgC) injected in the atmosphere (A,C) covers the range derived from airborne fraction $f \in (14, 45)$%, reference scenario (125 PgC) in bold. Injections in 100 yr with terrestrial $\delta^{13}C$ signature. In the filter function of the gas age distribution (B,D) the mean gas age varies from 320 yr to 480 yr with our chosen mean gas age of 400 yr in solid, representing the range given by the firn densification model.

MWP1A: The Flooding Hypothesis



Influence of the gas age distribution on the CH_4 synchronisation of EDC and NGRIP (Lemieux-Dudon et al. 2010). Considering the gas age distribution and the mean gas age in CO_2 leads to a synchronous start in the CO_2 rise around 14.8 kyr BP on the EDC age scale (lower x-axis) (Lemieux-Dudon et al. 2010). Due to a similar gas age distribution of CH_4 the synchronisation of ice core data contains a dating artefact which is for EDC at the onset of the B/A around 200 years. On the corrected age scale (upper x-axis) the onset in atmospheric CO_2 falls together with the earliest timing of MWP-1A (grey band) (Hanebuth et al. 2000; Kienast et al. 2003).



Areas flooded during MWP-1A. Changes in relative sea level from −96 m to −70 m are plotted from the most recent update (version 12.1) of global bathymetry (Smith & Sandwell 1997) with 1 min spatial resolution ranging from 81°S to 81°N.

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