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Two-phase change in CO_2, Antarctic temperature and global climate during Termination II

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The end of the Last Glacial Maximum (Termination I), roughly 20 thousand years ago (ka), was marked by cooling in the Northern Hemisphere, a weakening of the Asian monsoon, a rise in atmospheric CO_2 concentrations and warming over Antarctica. The sequence of events associated with the previous glacial–interglacial transition (Termination II), roughly 136 ka, is less well constrained. Here we present high-resolution records of atmospheric CO_2 concentrations and isotopic composition of N_2—an atmospheric temperature proxy—from air bubbles in the EPICA Dome C ice core that span Termination II. We find that atmospheric CO_2 concentrations and Antarctic temperature started increasing in phase around 136 ka, but in a second phase of Termination II, from 130.5 to 129 ka, the rise in atmospheric CO_2 concentrations lagged that of Antarctic temperature unequivocally. We suggest that during this second phase, the intensification of the low-latitude hydrological cycle resulted in the development of a CO_2 sink, which counteracted the CO_2 outgassing from the Southern Hemisphere oceans over this period.

The penultimate deglaciation (from about 136 to 129 thousand years before present (ka)) occurred under a different climatic and orbital context than the last deglaciation, characterized by larger glacial Eurasian ice sheets[1], a larger eccentricity and a different phasing between precession and obliquity[2]. The European Project for Ice Coring in Antarctica (EPICA) Dome C (EDC) ice core is ideally suited to identify the mechanisms at play during this time period thanks to the detailed climate and atmospheric composition information archived within about 100 m of ice. Ice cores record variations in local temperature through water stable isotopes in the ice phase, and variations in global atmospheric composition (for example, CO_2 and CH_4 concentrations) in the gas phase. Estimates of the age difference between the ice and the entrapped air are associated with uncertainties reaching several centuries[3]. To circumvent this difficulty, a profile of $\delta^{15}N$ in N_2 has been measured with an average resolution of 200 years for the period covering Termination II and the last interglacial period (~136–115 ka on the EDC3 timescale[4], Supplementary Information and Fig. 1).

Changes in $\delta^{15}N$ reflect past variations of firnification processes, largely driven by local temperature and accumulation, itself strongly linked to temperature in central Antarctica (see Supplementary Information). Our data reveal a very close correlation ($R^2 = 0.85$) between the $\delta^{15}N$ gas record and the ice δD, a proxy of local precipitation-weighted condensation temperature. This correlation is improved ($R^2 = 0.89$) when correcting δD for changes in oceanic moisture sources[5] (Fig. 1). Following refs 6,7, this change in $\delta^{15}N$ is assumed to be driven by a change in surface temperature and/or accumulation rate, giving access to changes in polar climate recorded in the same gas phase as changes in global atmospheric composition. Our assumption of concomitant changes in $\delta^{15}N$, Antarctic surface temperature and/or accumulation rate is consistent with the use of $\delta^{15}N$ as an indicator of the gas lock-in depth[8] that allows, after correction for ice thinning, a direct estimate of the ice age–gas age difference during Termination I (see Supplementary Information). This last approach cannot, however, be applied for Termination II owing to increasing uncertainty on ice thinning with depth. Using $\delta^{15}N$ as a climate proxy allows a precise quantification of leads and lags between changes in Antarctic climate and in atmospheric composition during Termination II. Existing CO_2 and CH_4 data[9,10] from the same EDC ice core were therefore complemented by new measurements to improve the resolution of the CO_2 record, and to characterize high-resolution variations of $\delta^{18}O_{atm}$ of O_2, a complex tracer integrating changes in global sea level, hydrological cycle and biosphere productivity[11] (Fig. 2).

The comparison of the evolutions of the CO_2 concentration and Antarctic temperature reveals two distinct phases within Termination II. Phase II-a is characterized by a parallel increase in CO_2 and Antarctic temperature. It is followed by phase II-b where atmospheric CO_2 concentration stabilizes around 260 ppm, preceding an abrupt increase to 285 ppm marking the end of phase II-b and the onset of the last interglacial. During phase II-b, the rate of Antarctic temperature increase is reduced compared with phase II-a. Our high-resolution records thus evidence a decoupling between the dynamics of CO_2 and Antarctic temperature over the two phases of Termination II. Within the uncertainty linked with the data resolution and variability, the

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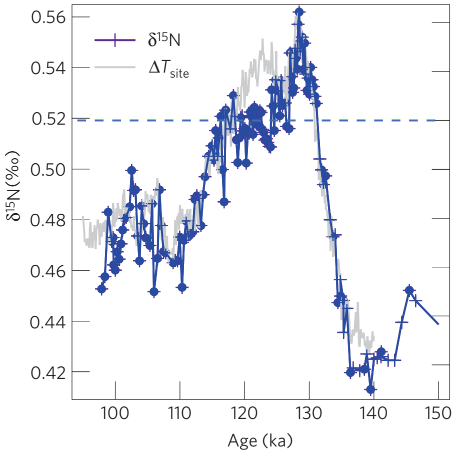

Figure 1 | Comparison of EDC $\delta^{15}N$ and T_{site} records on the EDC3 timescale. T_{site} has been calculated from the combination of ice $\delta^{18}O$ and δD (ref. 8). The vertical scales have been adjusted around the present-day levels of $\delta^{15}N$ and T_{site}. The horizontal dashed line indicates present-day levels of EDC $\delta^{15}N$ and T_{site}.

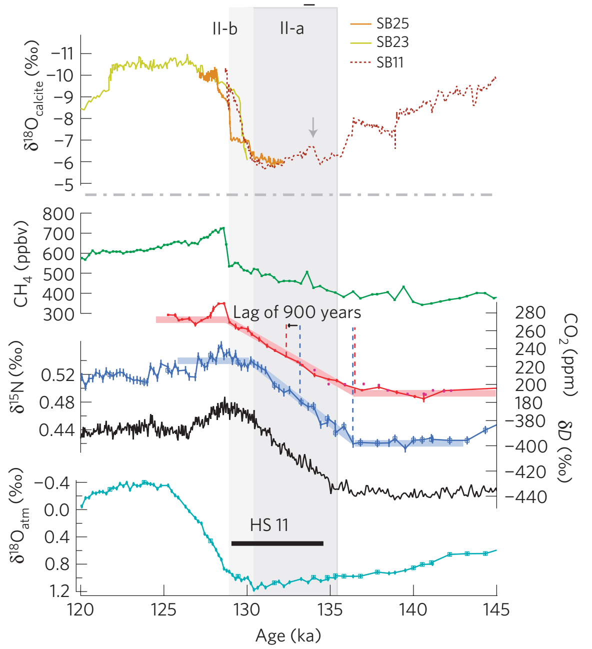

Figure 2 | Sequence of events over Termination II. From top to bottom are shown $\delta^{18}O_{calcite}$ from the Sanbao Cave[25,28] and EDC data records (CH_4 (ref. 10), CO_2 (ref. 9) with new data in purple, $\delta^{15}N$ (ref. 7) with new data in points, δD (ref. 4), and $\delta^{18}O_{atm}$ measured at Princeton with open squares and at LSCE with points). The horizontal dashed grey line highlights the change of timescale between speleothem and ice core records. The grey arrow indicates the interstadial event identified in the Sanbao Cave record[27] during Termination II. The ramps fitting CO_2 and $\delta^{15}N$ records (Supplementary Information) are indicated in light red and light blue, respectively. Standard deviations are indicated as error bars on the *y* axis.

onsets of deglacial $\delta^{15}N$ and CO_2 changes occur simultaneously. At mid-slope, there is an unequivocal lead of $\delta^{15}N$ over CO_2 of 900 ± 325 yr. This lead is slightly reduced to 675 ± 350 yr when considering the radiative forcing caused by changes in CO_2 (see Supplementary Information). This different behaviour of CO_2 and Antarctic temperature contrasts with CO_2 evolving in parallel with Antarctic temperature over Termination I (refs 12,13). Whereas earlier studies relying on firn models had reported a significant lead of Antarctic temperature on CO_2 during Termination I (for example, 800 ± 600 yr; ref. 14), the latest study using $\delta^{15}N$ data to constrain the gas ice–ice age difference[13] has depicted a synchronous rise in CO_2 and Antarctic temperature at the beginning of the termination and a lead of Antarctic temperature by 260 ± 130 yr only at the beginning of the Bølling–Allerød (B/A). Over Termination III, an average lead of 800 years of Antarctic temperature on CO_2 was identified using a methodology similar to ours[6] but the low resolution of the records did not allow assessment of the stability of this lead through time. From the differences between the high-resolution records of Termination I and Termination II, we conclude that Antarctic temperature and CO_2 are less closely related during Termination II than during Termination I.

Different mechanisms have been proposed to explain the simultaneous increase of CO_2 and Antarctic temperature over terminations, consistent with the sequence of events over Termination I (ref. 15). The first one describes terminations as a super Dansgaard–Oeschger (D/O) event[16] with Atlantic meridional overturning circulation (AMOC) change leading to a bipolar see-saw[17]. In this view, North Atlantic cooling is associated with Southern Ocean (and Antarctic) warming and associated outgassing of CO_2. The second one is based on atmospheric teleconnections with increased winter Northern Hemisphere sea ice and concomitant southward shifts of the intertropical convergence zone and southern westerly winds leading to both an outgassing of CO_2 in the Southern Ocean[18] and Antarctic warming. A third mechanism invokes brine formation on the Antarctic margins[19]. The maximum expansion of the Antarctic ice sheet could stop brine formation, leading to CO_2 outgassing leading to simultaneous Antarctic warming through the added greenhouse effect. All of these mechanisms can explain parallel rises in CO_2 and Antarctic temperature observed during Termination I and phase II-a of Termination II, but cannot account for a rise of Antarctic temperature without an associated increase in atmospheric CO_2 concentration as identified during phase II-b.

The transition between phase II-a and phase II-b is also identified by an inflection towards a significant rise in the $\delta^{13}C$ record of CO_2 (refs 9,20), probably reflecting a change in AMOC strength, a northward shift of westerlies in the Southern Ocean and then reduced upwelling and CO_2 outgassing or an increase in terrestrial or marine biological productivity[9,20–22].

To shed light on possible mechanisms at play during phase II-b, we now take advantage of our $\delta^{18}O_{atm}$ record. $\delta^{18}O_{atm}$ depends on the isotopic composition of water used by marine and terrestrial plants for their respiration. It is therefore sensitive to changes in continental ice volume that control seawater $\delta^{18}O_{sw}$ and indirectly all meteoric waters[23,24]. At precessional and millennial scales, strong similarities have recently been identified between $\delta^{18}O_{atm}$ and Chinese speleothem calcite $\delta^{18}O$, reflecting changes in the East Asian monsoon[24–26]. At these timescales, the low-latitude hydrological cycle is therefore believed to control changes in $\delta^{18}O_{atm}$ through its impact on meteoric water isotopic composition and global oxygen production.

We first summarize the structure of $\delta^{18}O_{atm}$ changes along Termination I (Fig. 3). During Heinrich Stadial 1 (HS1; ref. 27), $\delta^{18}O_{atm}$ shows a slight increase, very likely reflecting the fingerprint of the Weak Monsoon Interval[28] (WMI). It decreases at the onset of the B/A, assumed to coincide with the resumption of AMOC at the end of HS1 and the end of WMI (ref. 15). The first phase of Termination II (II-a) is associated with an increase of $\delta^{18}O_{atm}$. At the beginning of phase II-b, $\delta^{18}O_{atm}$ stopped increasing, thus marking a clear inflection point and is followed by a slow $\delta^{18}O_{atm}$ decrease over phase II-b. This slow decrease, close to a plateau between 130 and 129 ka, coincides with the plateau of CO_2 concentration, when CH_4 concentrations remain intermediate but Antarctic temperature is rising. By analogy with Termination I (phases I-a and I-b), this

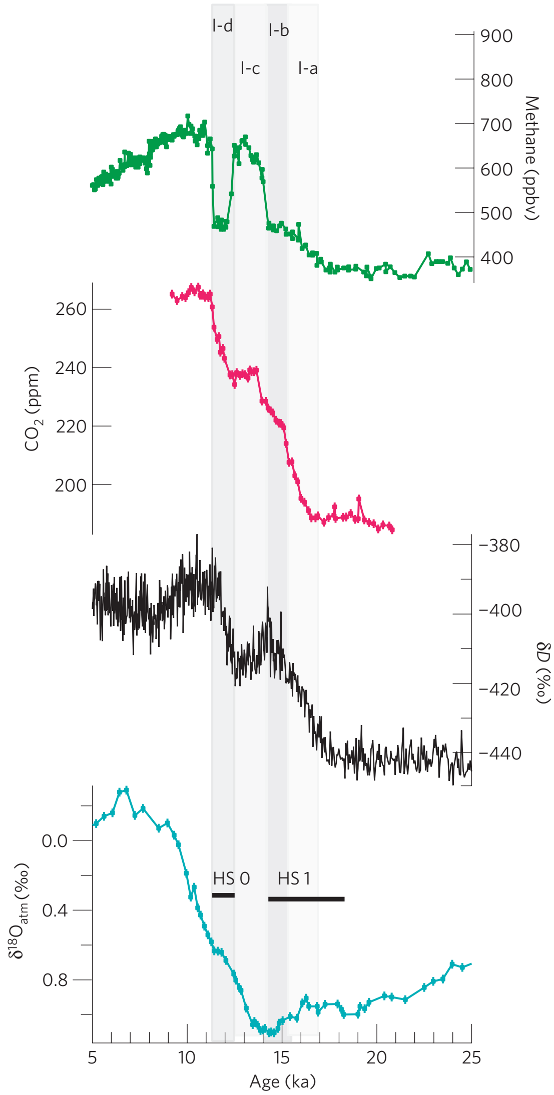

Figure 3 | Sequence of events over Termination I. From top to bottom are shown EDC data records (CH_4 (ref. 10), CO_2 (ref. 9), δ*D* (ref. 37) and $\delta^{18}O_{atm}$). The location of HS1 is indicated[27], as well as phases I-a, I-b, I-c and I-d corresponding to phases 1, 2, 3 and 4 of ref. 14.

pattern of CH_4 and Antarctic temperature could be explained by a weak AMOC and reduced Northern Hemisphere monsoons. However, the weak monsoon periods of Termination I (phases I-a and I-b) are characterized by an increase in $\delta^{18}O_{atm}$, in contrast with the decreasing $\delta^{18}O_{atm}$ during phase II-b.

Within age scale uncertainties, phase II-b may correspond to the ∼1.5 kyr pause identified during the second half of Termination II (refs 28–30) in some deep sea sediment and sea-level records. In well-dated and high-resolution Chinese speleothem calcite $\delta^{18}O$ data[28,31] (Fig. 2), Termination II is depicted by a first long weak monsoon phase (WMI-II, corresponding to HS11) perhaps punctuated by a brief multi-centennial wet phase at 134 ka (ref. 28). The abrupt end of Termination II is identified in a sharp decrease of calcite $\delta^{18}O$ at 129 ka (ref. 28). Using the high-resolution record from Sanbao Cave[28], a first 1‰ step drop in calcite $\delta^{18}O$ precedes by about 1.5 kyr the main sharp decrease of 3‰ at 129 ka (SB25, Fig. 2). Consistent with the 2 kyr uncertainty between the chronology of ice cores and speleothems over Termination II (ref. 32), we propose that the first Sanbao calcite $\delta^{18}O$ drop at 130.5 ka corresponds to the inflection point in $\delta^{18}O_{atm}$ and hence to the transition between phases II-a and II-b.

Together, these palaeoclimate records evidence a climate event that affected the global carbon and oxygen cycles as well as the global atmospheric composition over 1.5–2 kyr before the end of Termination II. During Termination I, the relatively small lag between Antarctic temperature and CO_2 has been attributed to the response time of the ventilation of the Southern Ocean[13,19,21,22,33]. The same mechanism may be at play during phase II-a, with a weak AMOC corresponding to a Heinrich stadial[34] associated with Antarctic warming and CO_2 degassing from the Southern Ocean. Our new data, however, point to a different process during phase II-b of Termination II, which has no analogue during Termination I.

We now investigate the processes that may explain the slowdown of the atmospheric CO_2 concentration when Antarctic temperature is rising, during phase II-b. At the beginning of phase II-b, the global $\delta^{18}O_{atm}$ and the calcite $\delta^{18}O$ record from Sanbao Cave consistently point to an intensification of the Northern Hemisphere low-latitude hydrological cycle. This water cycle intensification is possibly associated with a slightly strengthened AMOC and change in productivity (as suggested by $\delta^{13}C$ of CO_2; refs 20,21) possibly corresponding to a transition from a Heinrich stadial to a D/O stadial[34] and/or a reduced Northern Hemisphere sea-ice extent. We propose that the change in low-latitude climate enhanced the low-latitude carbon sinks owing to changes in the biosphere productivity and the ocean–atmosphere CO_2 exchange[35], which compensated the CO_2 degassing from the warming Southern Ocean, explaining the observed plateau of CO_2 concentration. The significant rise in $\delta^{13}C$ of CO_2 observed at that time[20] is in line with this interpretation, either through a low-latitude carbon uptake process or resulting from a slight decrease in CO_2 deep water outgassing in the Southern Ocean following a northward shift of westerly winds[22].

The end of phase II-b and hence of Termination II is then characterized by a strong enhancement of the low-latitude hydrological cycle, tracked by a steeper decreasing rate of $\delta^{18}O_{atm}$ and the large decrease of Sanbao Cave[28] calcite $\delta^{18}O$ probably coincident with a large AMOC strengthening. In our Antarctic records, it is clearly identified through an abrupt rise in CH_4, peak Antarctic temperature and CO_2 concentration. This final abrupt increase in CO_2 concentration is also concomitant with an abrupt shift in deuterium excess, a proxy of Antarctic moisture source shifts[36]. This suggests that the end of phase II-b is associated with an abrupt shift in southern westerlies favouring a final CO_2 outgassing from the Southern Ocean that is no longer counteracted by low-latitude sinks.

Why are the sequences of events different during HS1-Termination I and HS11-Termination II? These two terminations occur under different orbital contexts and the duration of HS11 is estimated to have been twice longer than HS1 (refs. 27) (6 kyr versus 3 kyr). The higher eccentricity during Termination II strengthens the magnitude and rate of changes in Northern Hemisphere summer insolation, compared with Termination I (ref. 2). Climate models relate freshwater fluxes and AMOC intensity. A stronger rate of retreat of the Laurentide ice sheet may therefore have maintained a reduced AMOC for a longer time during Termination II compared with Termination I, where an early AMOC recovery corresponding to the B/A is interrupted by HS0 leading to the Northern Hemisphere Younger Dryas cooling. Do these differences in AMOC histories have different impacts on the carbon cycle through different rates of Southern Ocean destratification and CO_2 outgassing? Does the orbital context of Termination II explain a larger response of the low-latitude water cycle at the end of Termination II? The new questions unveiled thanks to the detailed global sequence of events during Termination II should be tested using Earth system models, expanding the possibility to test climate and carbon cycle mechanisms during two different transitions.

Methods

Data. Data presented here are available through the NOAA/WDC Paleoclimatology archive at http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1::::P1_STUDY_ID:15077.

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Author contributions

A. Landais, J.J. and V.M-D. formulated the project. A. Landais, G.D., E.C., F. Prié and G.T. performed the measurements. A. Landais, G.D., E.C., J.J., V.M-D., D.M.R., N.C., J.C., M.L., A. Lourantou, F. Parrenin and D.R. performed the analysis and contributed to the writing and polishing of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A. Landais.

Competing financial interests

The authors declare no competing financial interests.