Abrupt change of Antarctic moisture origin at the end of Termination II


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The deuterium excess of polar ice cores documents past changes in evaporation conditions and moisture origin. New data obtained from the European Project for Ice Coring in Antarctica Dome C East Antarctic ice core provide new insights on the sequence of events involved in Termination II, the transition between the penultimate glacial and interglacial periods. This transition is marked by a north–south seesaw behavior, with first a slow methane concentration rise associated with a strong Antarctic temperature warming and a slow deuterium excess rise. This first step is followed by an abrupt north Atlantic warming, an abrupt resumption of the East Asian summer monsoon, a sharp methane rise, and a CO2 overshoot, which coincide within dating uncertainties with the end of Antarctic optimum. Here, we show that this second phase is marked by a very sharp Dome C centennial deuterium excess rise, revealing abrupt reorganization of atmospheric circulation in the southern Indian Ocean sector.

The Younger Dryas (YD) cold interval is likely caused by a freshening of the northern North Atlantic and a collapse of the AMOC (5, 6). Termination I abrupt events are also strongly imprinted in East Asian summer monsoon (EASM) activity (Fig. 1D) (7) and atmospheric methane concentrations (Fig. 1E) (8). During Termination I, the EDC δD (Fig. 1B) undergoes a first increase toward the Antarctic Isotopic Maximum AIM1, interrupted by the Antarctic Cold Reversal—the counter part of B-A warming, and followed by a second increase toward an early Holocene optimum peak (AIM0), which coincides with the AMOC resumption at the end of YD (5).

By contrast, EDC δD (Fig. 2B) shows a steady increase along Termination II. This termination is marked by the occurrence of the Heinrich 11 (H11) event (Fig. 2H) ending when the Antarctic temperature has already reached interglacial levels, and a likely reduced AMOC for the duration of the deglaciation (9, 10). Although there is evidence for reversals in some records of sea level (11), in eastern North Atlantic ocean surface temperature (12), and a short interstadial (Chinese interstadial B.1, lasting several centuries at ~134 ka, thousand years before present) in the EASM (7), most northern hemisphere records display cold conditions during H11 (phase 1) followed by a sharp temperature rise at ~129 ka (9) (phase 2). Within dating uncertainties (SI Appendix B), the rapid northern hemisphere temperature rise coincides with an abrupt increase in atmospheric methane (Fig. 2E) (8), suggested to be linked with an abrupt resumption of the EASM (Fig. 2D) (13). As during Termination I, the abrupt northern hemisphere warming (Fig. 2F and G) coincides with the end of the Antarctic temperature optimum, in a bipolar seesaw pattern. Between their peak warmth and the following cooling, AIM0 and 1 and this Termination II AIM are indeed fully comparable in magnitude (typically 1–2°) and in duration to...
Fig. 1. Comparison of records of Termination I. A coherent Greenland and Antarctic glaciological age scale is used (36). From top to bottom, (A) CO₂ concentration [ppm by volume, from Vostok, crosses (1), and from EDC (28, 37) circles]; (B) EDC δD (3) (%o, light gray); and (C) deuterium excess (%o against Vienna Standard Mean Ocean Water). Raw data measured along 55-cm samples were measured with a mean analytical precision of 0.5‰ at Laboratoire des Sciences du Climat et de l’Environnement (Lisbon, dark gray), 0.05‰ at Trieste and Parma (δ18O) giving access to deuterium excess (Bottom, gray). Smoothed records (δD, thick red; excess, thick blue) were produced from a nine-point binomial filter using 100-yr resampled data. Dashed vertical lines highlight abrupt deuterium excess rises during Termination I (AXR1a and AXR1b) detected using the RAMPFIT change-point regression method (see SI Appendix B). (D) Chinese Asian monsoon speleothem calcite δ18O (Hulu and Sanbao caves (7), different speleothem records available for Termination I are displayed with different colors of orange). (E) EPICA Dome C methane data (ppb by volume) from EPICA Dome C (thick green) (8). (F) North Atlantic SST (blue, Celsiu) from cores NA87-22 (38) (see SI Text). (G) Greenland NorthGRIP ice core δ18O, a proxy of Greenland temperature (see SI Appendix B). (H) Variations of obliquity (dotted dashed yellow line) and precession parameter (dashed yellow line) (reversed axis to be in phase with Northern Hemisphere summer insolation) are also displayed. (I) Ice rafted detritus (IRD) (lithics/dry sediment) (brown) data from core NA87-22 (38, 39). Long-dashed horizontal lines display the late Holocene temperature levels.

The glacial AIM events, attributed to the bipolar seesaw linked with changes in the AMOC (14). Combined δD and δ18O measurements conducted on the same samples of the EDC ice core have provided deuterium excess data (δ = δD − 8δ18O) and new insights on Dome C moisture source over the Holocene, the last deglaciation, and the last glacial period (15). Deuterium excess (16, 17) is an integrated tracer of the water cycle mainly influenced by kinetic fractionation effects taking place at the moisture source during evaporation, but also during droplet reevaporation and formation of ice crystals (SI Appendix A). The EDC deuterium excess record is now extended back to Termination II (Figs. 2C and 3) at much higher resolution (~50 yr) than the earlier Antarctic ice core data from Vostok (16) and Dome Fuji (18). Modeling studies using back trajectories as well as atmospheric general circulation models suggest that Dome C receives moisture transported from the temperate area of the southern Indian Ocean in contrast to other East Antarctic sites such as Vostok or Dome F, expected to receive a larger contribution from the Atlantic or Pacific sub tropics (19). Simulations show that the interglacial deuterium excess in central Antarctica is strongly linked with changes in the Southern Annular Mode (SAM) (20), as reduced westerlies weaken high-latitude evaporation and permit stronger advection of midlatitude moisture toward central Antarctica, resulting in a warmer moisture source and higher deuterium excess in modeled central Antarctica precipitation. Changes in EDC deuterium excess data therefore reflect both changes in evaporation conditions in its moisture source region and geographical shifts in moisture origin in relationship with atmospheric circulation. Our record adds to the understanding of climate dynamics by documenting changes affecting the south Indian Ocean area, with an unprecedented resolution over MIS5.5-6.

Termination II starts after ~140 ka, when Antarctic temperature (δD), deuterium excess, methane, and carbon dioxide start increasing from low glacial values (Fig. 2). The first warming phase (δD increase) is paralleled by a slow deuterium excess rise. The Antarctic warming is mimicked by parallel Austral ocean warming at mid and high latitudes (21–23). This small deuterium excess rise is interpreted as resulting from the compensation between a warming southern Indian Ocean (inducing higher excess) and an increasing contribution of high latitudes to EDC moisture (inducing a lower excess). In a second phase, when δD reaches an optimum, deuterium excess undergoes a drastic shift, at ~128.5 ka. This abrupt excess rise (AXR) event reaches a magnitude of 2.4‰ (half of glacial–interglacial amplitudes) within approximately a century (SI Appendix B), much larger than other secondary (~1‰) deuterium excess variations (detected
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**Discussion**

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**Material and Methods**

The sequences of events during Termination I (Fig. 1) and Termination II (Fig. 2) have been established using data previously published, as described in the figure captions, complemented by our records, and improved chronologies. We have produced North Atlantic SST reconstructions (see "SI SST Reconstructions"), and measurements of EDC ice core stable isotopes (as described in the caption of Fig. 3) in order to confirm the deuterium excess shift identified in the low-resolution data (15). We have placed all the Antarctic ice core records of Termination I on a common chronology (36) coherent with the Greenland Ice Core Chronology 05 reference age scale, and all the ice core records of Termination II (including the Greenland records) on the EDC3 age scale (see "SI Text") using gas synchronization. Termination II/last interglacial North Atlantic marine records have been placed on the EDC3 age scale.
scale by assuming synchronous temperature changes in the air above Greenland and in the North Atlantic, hence synchronizing its SST record to the North Greenland Ice Core Project (North-GRIP) ice δ¹⁸O record and the EPICA Dome C methane record (SI Common age scales for marine and ice records). We have used a specific objective statistical method for the detection of deuterium excess abrupt shifts [SI Timing of abrupt excess rise (AXR) events].

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