LETTERS
PUBLISHED ONLINE: 22 FEBRUARY 2009 | DOI: 10.1038/NGEO442

nature geoscience

Glacial terminations as southern warmings without northern control

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The change from a glacial to an interglacial climate is paced by variations in Earth's orbit[1]. However, the detailed sequence of events that leads to a glacial termination remains controversial. It is particularly unclear whether the northern[2,3] or southern[4–6] hemisphere leads the termination. Here we present a hypothesis for the beginning and continuation of glacial terminations, which relies on the observation that the initial stages of terminations are indistinguishable from the warming stage of events in Antarctica known as Antarctic Isotopic Maxima[7], which occur frequently during glacial periods. Such warmings in Antarctica generally begin to reverse with the onset of a warm Dansgaard–Oeschger event in the northern hemisphere[7,8]. However, in the early stages of a termination, Antarctic warming is not followed by any abrupt warming in the north. We propose that the lack of an Antarctic climate reversal enables southern warming and the associated atmospheric carbon dioxide rise to reach a point at which full deglaciation becomes inevitable. In our view, glacial terminations, in common with other warmings that do not lead to termination, are led from the southern hemisphere, but only specific conditions in the northern hemisphere enable the climate state to complete its shift to interglacial conditions.

Both the ice-core[9] and marine[10] records show that the most prominent climate signal of the past 800,000 years is the alternation between long cold periods, and short periods of interglacial warmth, recurring approximately every 100,000 years (Fig. 1a). Investigation in the frequency domain suggests that seasonal and latitudinal variations in insolation due to changes in Earth's orbit pace the observed changes[1], and the strength of major warmings implies that amplification, especially through albedo and greenhouse gas changes[11], is essential. However, the reason for the spacing and timing of interglacials, and the sequence of events at major warmings, remains obscure. In most terminations, warming in Antarctica proceeds fairly steadily over several millennia[9], accompanied by increasing CO_2 (refs 11,12), and decreasing deepwater isotopic values[10] (representing deepwater temperature and ice volume). For the most recent termination (TI), Greenland[13] temperature changed little during the Antarctic warming (Fig. 1b), jumping abruptly towards interglacial levels (towards the Bolling warm period) only rather late in the termination. In other terminations, if we treat rapid changes in methane[14] as a proxy for rapid changes in Greenland temperature, a rapid northern-warming step coincided with the completion of Antarctic warming (Fig. 2).

It is customary to seek a cause for either northern or southern warming to initiate uniquely at terminations. However, there are numerous periods of significant Antarctic warming during

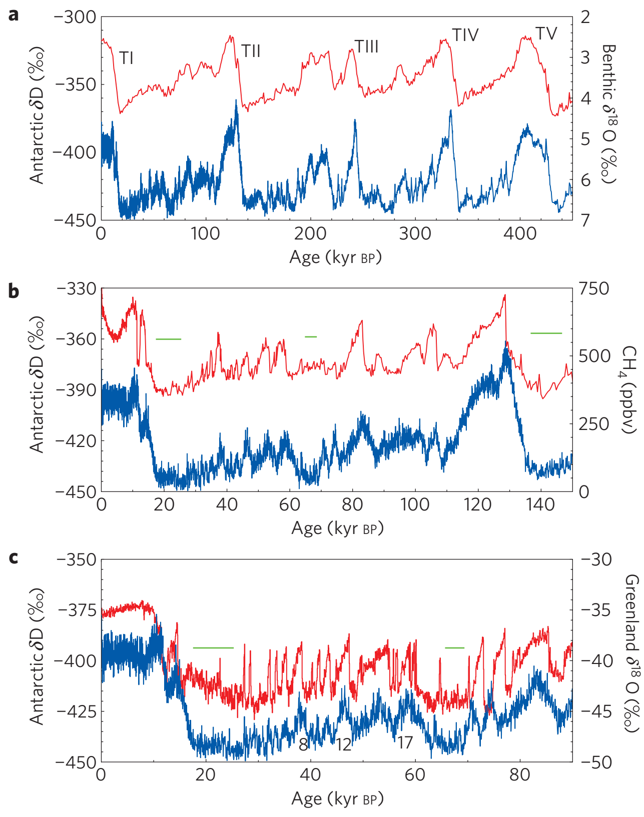

Figure 1 | Climate records over the past 450, 150 and 90 kyr. **a**, Deuterium from Dome C, Antarctica[9] (blue, lower curve, EDC3 age scale); benthic δ^{18}O stack[10] (red, LR04 age scale). TI–TV denote terminations. **b**, Dome C deuterium[9] (blue, lower curve) and methane (red, EDC3_gas_a age scale[14]). Methane is given in units of parts per billion (parts per 10^9) by volume (ppbv). **c**, Dome C deuterium[9] (blue, lower curve); NorthGRIP δ^{18}O (Greenland, red) on the NGRIP age scale[13]. AIM 8, 12 and 17 are marked. The age scales in **c** are not synchronised: significant mismatches probably occur below 60 kyr. Green horizontal bars (**b**, **c**) denote periods with minimal Antarctic Isotopic Maximum or DO activity.

the glacials[7]. In the stronger ones, known as A-events, a clear sequence was observed, in which Antarctica, and presumably the Southern Ocean, warmed as long as the north (Greenland) was in a Dansgaard–Oeschger (DO) cold phase; when Greenland jumped into a DO warm phase, Antarctica cooled again[8]. Recently it was proposed that Antarctic warmings (Antarctic Isotopic Maxima,

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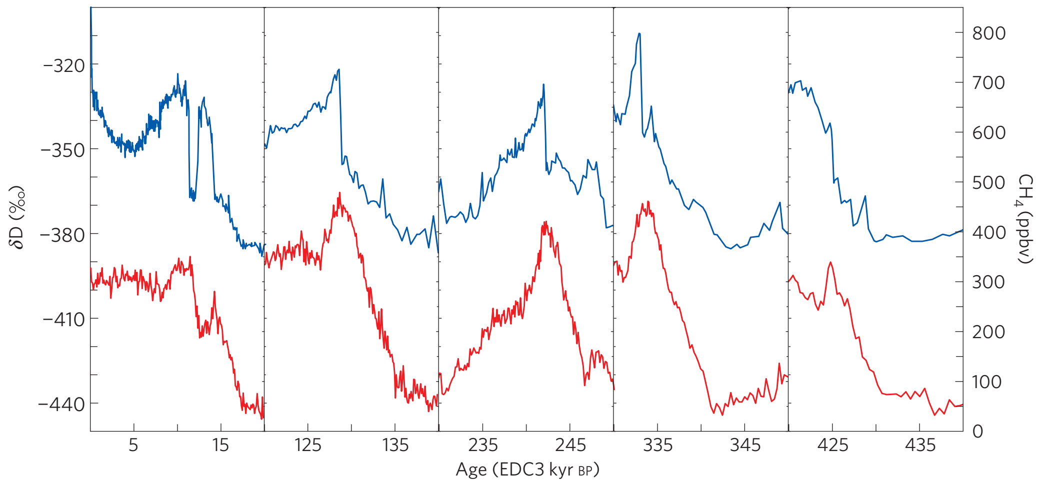

Figure 2 | Terminations in Antarctic deuterium and in methane. From the Dome C, Antarctica ice core, deuterium[9] (red, lower curve, representing Antarctic temperature) and methane[14] (blue, upper curve) are shown for the five most recent terminations. Methane is given in units of parts per billion by volume (ppbv). Within the uncertainty of the gas-age–ice-age difference, the very fast jump in methane coincides with the end of Antarctic warming, just as it does in AIM.

AIM) are associated with each of the 25 identified DO events[7]. Although the timing of the smaller Antarctic Isotopic Maximum events could not be precisely determined, the amplitude of AIM was linearly related to the duration of DO cold[7].

The statements above describe observations from a northern viewpoint: Antarctic events are counterparts to northern DO events. A different insight comes from re-stating the same information from a southern perspective: Antarctica warms in AIM at a steady rate until a DO event occurs and the warming reverses. What we mean is that a climate switch, generally assumed to be oceanic, occurred, and was manifested as an instantaneous rise in Greenland temperature and a reversal in Antarctic temperature. For simplicity, we will use the DO warming as diagnostic of the switch, and refer to the switch as a DO 'event'.

We now compare terminations with AIM warmings (Fig. 3), testing the generality of the assertion that TI was initiated by an Antarctic Isotopic Maximum fluctuation in Antarctic temperature, CO_2 and overturning[15]. We use larger AIM (A-events) but assume[7] that smaller AIM are small-scale versions of them, reversed by a DO event earlier in their life. We use AIM only from the most recent glacial cycle, where they have been clearly identified. Nonetheless, there are strong indications[9,14,16] that similar features occurred in earlier cycles. The rate of Antarctic warming at Dome C (Fig. 3) in AIM is within the range ($\sim$5–10‰ kyr^{-1} in deuterium) of that observed in the early parts of terminations[17]; this is also true if we compare the rate of warming for TI and AIM 8 and 12 at the EPICA DML site[7]. The accompanying CO_2 change[12,18] (signifying aspects of Southern Ocean conditions) is similar in terminations and AIM for a comparable temperature (Fig. 4), although we cannot determine the phasing between CO_2 and Antarctic temperature sufficiently well to claim similar timing. For calcium fluxes to Antarctica (representing dust transported from South America)[19,20], similar proportional changes occur in the first 1,500 years of TI and in AIM 8 and 12 (Fig. 4), whereas sodium fluxes, which change significantly later in terminations, hardly change in AIM or the early parts of terminations. In high-resolution records[21], changes in marine benthic ^{18}O for the large AIM (ref. 10) proceed at the same pace as in the early parts of terminations (Fig. 4). Methane shows a small drift upwards during the early parts of terminations, that is not seen in most AIM, but because it drifts slowly down during the preceding glacial maxima it still remains at or below absolute levels seen during comparable stages of AIM.

In short, the first approximately 1,500 year period of terminations is almost indistinguishable from the warming phase of a strong Antarctic Isotopic Maximum (Fig. 3b), proceeding at a similar rate, and with the same relationship between different parts of the Earth system. The most parsimonious assumption is that the mechanism of warming is the same. If this is true, we need not ask why southern warming occurs at terminations, because it occurs many times during each glacial. Rather we need to ask why it does not halt, as it does during AIM, apparently in response to a DO event.

In terminations, DO events occur only when so much time has elapsed that the south, and associated parameters with global implications (notably CO_2 concentration), have reached interglacial levels, ensuring that the entire system is committed to transition. In four of the five most recent terminations, a rapid methane jump occurs coincident with the end of Antarctic warming (Fig. 2). On the basis of the most recent climatic cycle, jumps (but not slow trends) in methane are characteristic of DO events, coinciding with rapid Greenland warming; this interpretation is reinforced by the fact that rapid rises in sea-surface temperatures in marine cores from the Portuguese margin are also observed near the end (in the benthic oxygen isotope signal) of TII, III and IV (ref. 16). The only exception is TI, where the Bolling warming (and its associated methane increase and Portuguese margin sea-surface temperature rise) occurred late in the termination, causing a brief reversal (Antarctic Cold Reversal), but the warming and other feedbacks had already passed the point of no return by then. The difference between a termination and AIM is that DO warming occurs later, and it is this delayed appearance of a DO jump that requires a physical explanation.

Our insight implies that warmings are led from the south, but it is events (or the lack of them) in the north that enable the warming to continue beyond control and to interglacial conditions. If the cause of southern warming at terminations is similar to that during AIM, given the suborbital period of earlier AIM, we must assume that this timing is not orbitally controlled. However, the conditions that delay a DO event may be under orbital control.

Although our work leads to a proximal cause for a termination (non-appearance of a DO event to halt southern warming), this poses the question of what it is about the conditions at terminations that prevents or delays a DO event. We note that there is a substantial period before terminations during which the bipolar seesaw[22] seems to not be operating (Fig. 1), with neither DO

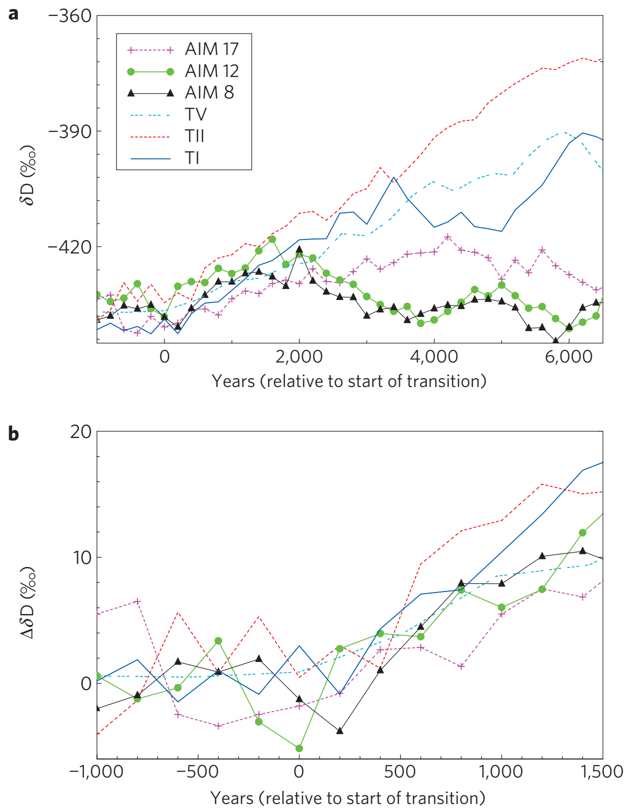

Figure 3 | Three terminations and three Antarctic Isotopic Maximum warmings in Dome C deuterium. Age is zeroed to the start of each warming, determined by a ramp fit[17,27] on unsmoothed data, except for AIM 8, where the shape of the warming made this approach inappropriate. 200-year averages are plotted, except for TV, where raw data of similar resolution are used. **a**, Complete AIM and most of each termination. **b**, The start of each event; deuterium values are referred to the ramp-fit value for the onset of warming, to enable easier comparison of warming rates. Supplementary Fig. S1 shows the five most recent terminations.

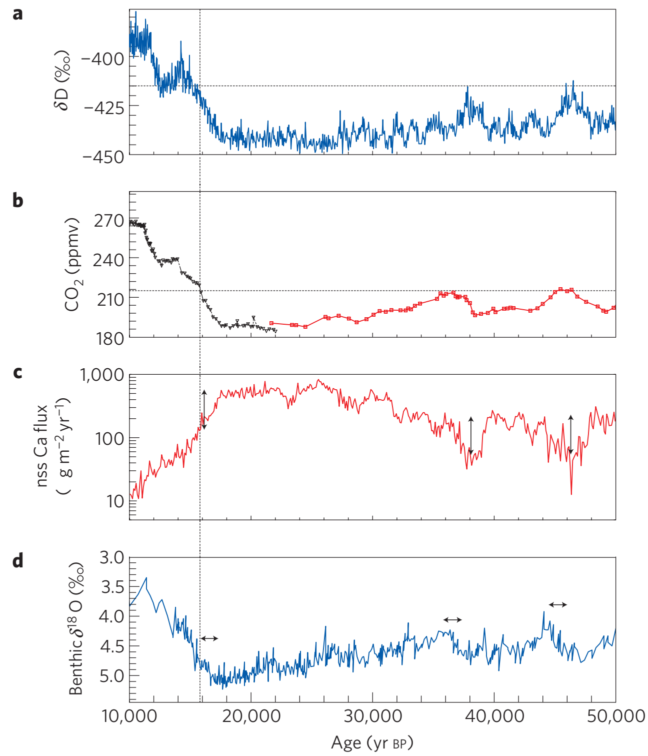

Figure 4 | Termination I and two large AIM. a, Dome C deuterium[9]; **b**, Dome C (ref. 28) (black) and Taylor Dome[18] (red) CO_2, with Taylor Dome data shifted to the EDC3 age scale using Taylor Dome–Vostok[18] and Vostok–Dome C (ref. 29) chronological links. Carbon dioxide is given in units of parts per million by volume (ppmv). Grid lines mark maximum Antarctic Isotopic Maximum CO_2 and deuterium values, also reached simultaneously in TI. **c**, Dome C non-sea-salt calcium fluxes[19,30]; arrows mark a fixed logarithmic change in flux. **d**, Benthic oxygen isotope data (core MD95-2042, Iberian Margin)[21], on the core's own age scale; events identified as AIM 8 and 12 are therefore displaced from the other records; arrows mark a fixed time period.

warmings, nor AIM, occurring. Such periods, typically around 10 kyr long, are common to the past five glacial maxima (beyond this, data resolution prohibits a definite conclusion), but occur at least once in a period well removed from any termination (~60–70 kyr). The periods without either AIM or DO warmings seem to always coincide with both the most pronounced southern cold, and the largest northern ice volumes.

This suggests two possible scenarios. First, it has been proposed that receding sea-ice cover around Antarctica, resulting from slow warming during early stages of deglaciation, is the trigger for the resumption of Atlantic meridional overturning circulation and associated DO warmings[5]; by implication, this would also apply to AIM. If highly extended and perhaps perennial sea-ice cover were maintained during the coldest periods, it might require a longer period of subsequent warming and sea-ice retraction to enable the salt and water flow to the North Atlantic to trigger a full resumption of Atlantic meridional overturning circulation. A mechanism enabling simultaneous northern and southern cooling, with maintenance of Antarctic sea ice[23], has been proposed, involving a reduction in Southern Ocean wind strength, although there is no evidence that this occurred. The second possibility is that the large ice volume in the north somehow prevents a DO warming from occurring: the interaction of ice extent and sea-ice conditions in one of the critical areas of the ocean in the north might be implicated. For this northern mechanism, our proposal that it operates through suppression of DO warming puts one mechanistic step into conceptual models suggesting that terminations occur only when ice-sheet volume is above a threshold[24]. In any case, it is now necessary to assess whether recent hypotheses[6,25] about the orbital conditions for termination, or alternatively one suggesting a synergy between overturning and burial of $CaCO_3$ (ref. 15), could account for the mechanistic sequence of events we have described, including the cessation of Antarctic Isotopic Maximum/DO activity before the termination.

There seems to be a threshold in Antarctic conditions, above the maximum of an Antarctic Isotopic Maximum, but below that occurring just before the Antarctic Cold Reversal, beyond which the climate redistribution of Antarctic Isotopic Maximum/DO pairs changes into a full termination. We still need a more distal cause to understand the timing of terminations. Although there are other periods of low insolation when DO/Antarctic Isotopic Maximum activity seems to persist, the periods we identify do all correspond to times of low northern-hemisphere summer insolation. This might suggest that the insolation state in glacial maxima, rather than the trend during terminations, is significant.

In summary, the sequence at glacial terminations (see Supplementary Fig. S2) is: (1) After a run of paired Antarctic Isotopic Maximum and DO events, neither occurs for several millennia. In TI this starts at ~26 kyr, and during it Greenland warms slowly. This period of extreme southern cold, combined with northern ice-sheet growth in the absence of a DO event, seems to disable the system from producing a DO event early in the next southern warming. (2) Eventually Antarctic warming does begin, and follows the same initial course as in AIM. In TI, this begins at ∼17.6 kyr (EDC3 age scale), almost simultaneous with Heinrich event H1 (ref. 26). (3) No DO event is produced, and southern warming continues, with associated events including increasing CO_2. (4) Only when southern warming has proceeded significantly towards interglacial levels does a DO event occur, either ending the warming (in TII, TIII and TIV) or causing a temporary reversal of magnitude similar to the cooling from an Antarctic Isotopic Maximum (TI, TV).

Warming at terminations, as at each Antarctic Isotopic Maximum, is led from the south, but events in the north enable the warming to continue unchecked. The proximal cause of deglaciation is therefore northern conditioning, which paradoxically prevents an early northern DO warming. Although model-based tests are required of our two hypotheses about why the sequence begins (with the cessation of the bipolar seesaw), this work advances understanding of terminations by suggesting that terminations are caused by southern warming that runs away because the north cannot produce a DO event.

Received 23 December 2008; accepted 27 January 2009; published online 22 February 2009

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Acknowledgements

This work is a contribution to the European Project for Ice Coring in Antarctica (EPICA), a joint European Science Foundation/European Commission scientific programme, funded by the EU and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland and the United Kingdom. The main logistic support was provided by IPEV and PNRA (at Dome C) and AWI (at Dronning Maud Land).

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