Expression of the bipolar see-saw in Antarctic climate records during the last deglaciation

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Ice-core records of climate from Greenland and Antarctica show asynchronous temperature variations on millennial timescales during the last glacial period[1]. The warming during the transition from glacial to interglacial conditions was markedly different between the hemispheres, a pattern attributed to the thermal bipolar see-saw[2]. However, a record from the Ross Sea sector of East Antarctica has been suggested to be synchronous with Northern Hemisphere climate change[3]. Here we present a temperature record from the Talos Dome ice core, also located in the Ross Sea sector. We compare our record with ice-core analyses from Greenland, based on methane synchronization[4], and find clearly asynchronous temperature changes during the deglaciation. We also find distinct differences in Antarctic records, pointing to differences in the climate evolution of the Indo-Pacific and Atlantic sectors of Antarctica. In the Atlantic sector, we find that the rate of warming slowed between 16,000 and 14,500 years ago, parallel with the deceleration of the rise in atmospheric carbon dioxide concentrations and with a slight cooling over Greenland. In addition, our chronology supports the hypothesis that the cooling of the Antarctic Cold Reversal is synchronous with the Bølling–Allerød warming in the northern hemisphere 14,700 years ago[5].

The period from about 8 to 25 kyr before present (BP) includes the climate transition from the last glacial to the Holocene. As documented from polar ice cores and other climate archives, the pattern of climate changes throughout this transition is different between Antarctica and the surrounding Southern Ocean and the Northern Hemisphere. The steady Antarctic deglacial warming reaches a first maximum (Antarctic Isotopic Maximum AIM1; ref. 1) followed by an interruption towards cooler conditions during the Antarctic Cold Reversal (ACR). Conversely, Greenland records show two rapid-warming phases at the onset of the Dansgaard–Oeschger-1 (DO1) event (Bølling–Allerød interstadial, B/A) and the Holocene, separated by the Younger Dryas (YD) cold event[5,6]. This different sequence of events in the two hemispheres was related to the thermal bipolar see-saw[1,2].

A prerequisite for studying the sequence and possible links between climate events in Greenland and Antarctica is the determination of their relative timing with sufficient accuracy[7]. For sites located on the East Antarctic Plateau (EAP), high-resolution CH_4 records[4] have been used to place the European Project for Ice Coring in Antarctica (EPICA) Dronning Maud Land (EDML), and by extension the EPICA-Dome C (EDC) and Vostok, Antarctic ice cores[8], on the layer-counted Greenland Ice Core Chronology 2005 (GICC05; see Supplementary Information). Although ice cores from the EAP show a coherent picture[1,9,10], coastal ice cores are expected to be influenced by regional signals related to the surrounding ocean. So far, few ice cores from peripheral sites[3,11] cover the last deglaciation. Critical for these coastal sequences is the relative depth of the last deglaciation with respect to bedrock, where ice thinning and deformation can perturb the stratigraphy. Furthermore, the extremely high variability of strong wind scouring can induce accumulation hiatuses.

The end of AIM1 as deduced from EAP ice cores is in phase with the first rapid temperature change in Greenland[5] (14.7 kyr BP). This synchronicity supports the thermal bipolar see-saw conceptual model[2], but is in apparent contradiction with the timing of climate change shown by the Taylor Dome (TYD) ice core in the Ross Sea sector[3]. The timing of the stable isotope record from this coastal ice core seemed more similar to Greenland rather to Antarctic cores, with a first warming ending abruptly at ~14 kyr BP (ref. 3), although this dating was already questioned[12]. Another coastal ice core, Law Dome (LD, East Antarctica), conversely, ends the first warming at ~15 kyr BP, suggesting that the ACR does not follow the abrupt warming of DO1 (ref. 11). However, in this critical time interval, questions regarding the integrity of the timescale (TYD) and abrupt

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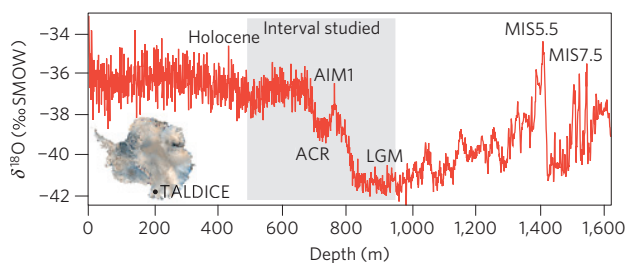
Figure 1 | The TALDICE stable isotope profile (δ^{18}O) versus depth. The interval studied (8–25 kyr BP) is marked with grey shading. MIS 5.5, 7.5, LGM, AIM1 and ACR are indicated. The satellite image of Antarctica shows the location of the TALDICE ice core.

reduction in accumulation and thus limited time resolution (LD) render some earlier conclusions questionable.

Here we investigate a new 1,620-m-deep ice core drilled at Talos Dome (TLD) in the framework of the Talos Dome Ice Core (TALDICE) project (www.taldice.org). TLD is a peripheral dome of East Antarctica, located in the Ross Sea sector (Fig. 1). The moisture sources for TLD are mainly located in the Pacific and Indian sectors of the Southern Ocean (see Supplementary Information). The whole TALDICE ice core provides a palaeoclimate record covering the past 250 kyr back to Marine Isotope Stage (MIS) 7.5 (Fig. 1). The TALDICE oxygen-isotope (δ^{18}O, a proxy of local temperature) record is presented here for the entire core (Fig. 1) and for the time window between 8 and 25 kyr BP (Fig. 2). TALDICE enables decadal-scale resolution during the last deglaciation owing to its relatively high accumulation rate (80 kg m^{-2} yr^{-1}). In this work, the TALDICE-1 chronology (see Supplementary Information) has been set up using a new inverse method[8], generating an optimal compromise between an a priori scenario set up from a glaciological model and chronological information from different time markers. CH$_4$ data are used to synchronize[4] TALDICE to the North Greenland Ice Core Project (NGRIP) ice core on the GICC05 age scale (see Supplementary Information), providing a relative synchronization error less than 100 yr for the sharp CH$_4$ transitions. TALDICE is the first coastal site with glaciological characteristics enabling accurate dating during the entire last deglaciation, which starts at around 800 m depth (∼50% of the total ice thickness; see Supplementary Information). The resulting chronological uncertainty is ±300 yr between 8 and 15 kyr, ±500 yr back to 17.5 kyr and up to ±1.5 kyr during the glacial period.

The pattern of δ^{18}O during deglaciation is similar at TALDICE and EDC (Fig. 2), despite their different geographical positions and moisture sources (see Supplementary Information). The transition starts synchronously at 18.2 ± 0.7 kyr BP in TALDICE, EDML, EDC and Dome Fuji (DF) records (Figs 2 and 3), a few kiloyears before the Antarctic ice-sheet margin retreat[13]. Warming appears coeval with the ages reported for mid-latitude glacier retreat from both hemispheres[14] and the rapid sea-level rise at 19 kyr BP (ref. 13). The first part of deglaciation culminates in the AIM1 event at 14.7±0.3 kyr BP, followed by the ACR cooling (Fig. 2) until 12.7 ± 0.3 kyr BP, and by the final warming towards the onset of Holocene. The ACR cooling appears with weaker δ^{18}O amplitude in TALDICE than in EDC.

TALDICE confirms that the TYD chronology[3] is almost certainly incorrect[12] and enables us to refute that the deglacial history in the Ross Sea area was synchronous with the Northern Hemisphere (Figs 2 and 3).

During the Last Glacial Maximum (LGM) and the deglaciation, the comparison of δ^{18}O records around Antarctica highlights regional features. Earlier studies revealed a smoother shape of glacial AIM events at EDML compared with EDC (ref. 15) as well as an identification of AIM2 at EDML–DF (refs 1,9) but not
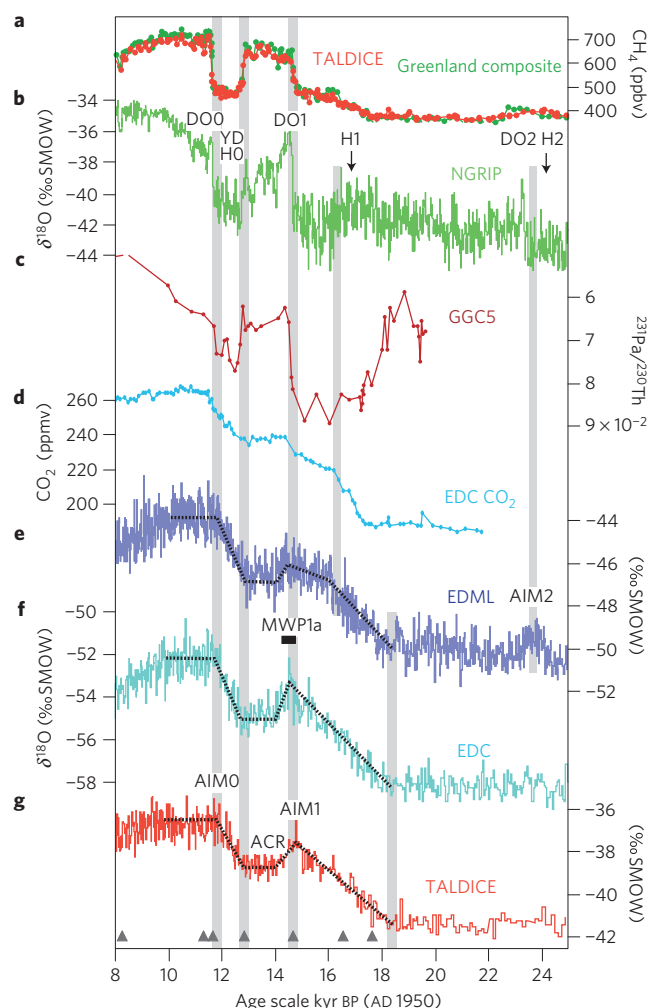

Figure 2 | Compilation of palaeoclimatic records from ice and marine cores to depict the bipolar sequence of events during the last termination. a, CH$_4$ records of Greenland composite[4] and TALDICE (this study); **b**, δ^{18}O record from NGRIP (ref. 6); **c**, ^{231}Pa/^{230}Th record of marine core GGC5, from Bermuda rise in the deep western subtropical Atlantic, taken as a proxy for Atlantic meridional overturning circulation strength[19]; **d**, CO$_2$ from EDC (ref. 18); **e**, δ^{18}O record from EDML (ref. 1); **f**, δ^{18}O record from EDC (ref. 10); **g**, δ^{18}O record from TALDICE (this study). EDML, EDC and TALDICE are synchronized on the GICC05 timescale using a new inverse method. GGC5 data are shown on their own radiocarbon timescale. The dotted lines correspond to the ramps obtained with the Rampfit and Breakfit software. The YD and DO interstadials are indicated[5,6]. The black horizontal bar corresponds to MWP1a (ref. 22); the arrows represent the ages of Heinrich layers 1 and 2. The triangles indicate synchronization CH$_4$ tie points. The grey vertical bars correspond to the AIM2 event, the start of the deglaciation (18.2±0.7 kyr BP), the slowing of the warming at EDML (16.0±0.2 kyr BP), the AIM1 event (14.7±0.3 kyr BP), the end of the ACR (12.7±0.3) and the AIM0 (11.9±0.3) event as inferred from δ^{18}O ice-core records (this study).

at EDC. The lack of an AIM2 signal in the Indo-Pacific sector is confirmed by the TALDICE data (Fig. 2). A specific deglacial pattern is observed in EDML–DF ice cores compared with EDC–TALDICE. These two last cores show a ∼3.5 kyr warming at an almost constant rate (1 and 1.3‰ δ^{18}O kyr^{-1}, respectively) peaking in AIM1, whereas EDML–DF depict a reduced warming rate (about 0.5‰ δ^{18}O kyr^{-1}) between 16.0 ± 0.2 kyr BP and AIM1 (Figs 2 and 3). This slowdown of the warming can be also depicted from EDC–TALDICE records but is negligible with respect to EDML–DF.
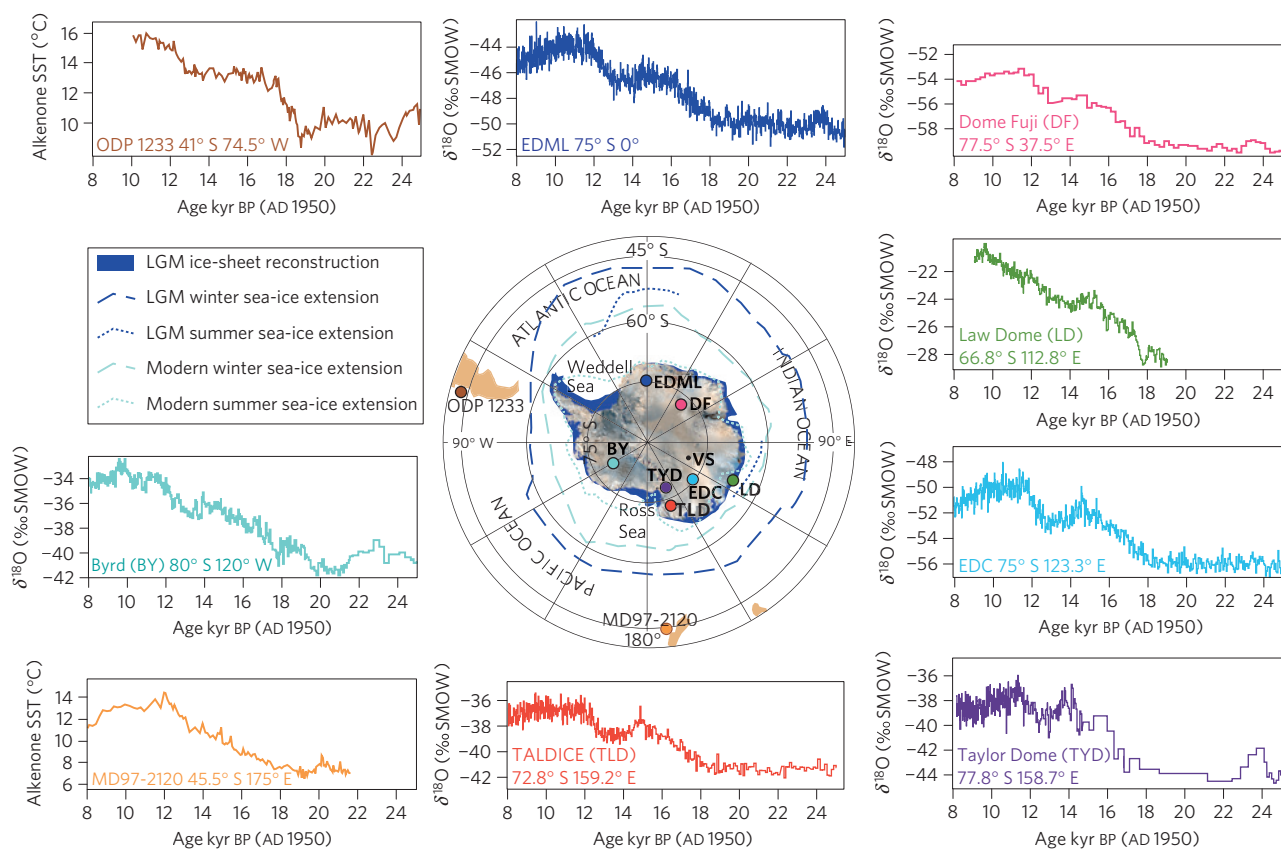
Figure 3 | Compilation of Southern Hemisphere palaeoclimatic records from ice and marine-sediment cores during the last deglaciation. From top left in clockwise order, alkenone-SST record from ODP 1233 (ref. 16); $\delta^{18}O$ record from EDML (ref. 1), DF (ref. 9), LD (ref. 11), EDC (ref. 10), TYD (ref. 3) and TALDICE (this study); alkenone-SST record from MD97-2120 (ref. 17); $\delta^{18}O$ record from Byrd[28]. EDML, EDC and TALDICE are synchronized on the GICC05 timescale using a new inverse method. DF, LD, TYD and Byrd data are shown on their own timescale. ODP 1233 data are shown on its timescale[16] and MD97-2120 on the timescale developed by ref. 29. The map also shows, with circles, the locations of the ice cores of the Antarctic Ice Sheet and sediment cores in the Southern Ocean cited in the text (VS: Vostok). In blue, a sketch of the LGM ice-sheet reconstruction. The blue and light-blue lines show LGM and modern winter (dashed lines) and summer (dotted lines) sea-ice extension[30], respectively.

Albeit hampered by the lack of coherent age scales, the comparison of the deglaciation $\delta^{18}O$ records obtained on various ice cores (Fig. 3) reveals regional site-specific patterns in terms of warming rates and magnitudes. A change in the rate of warming around 16.7 kyr BP is also observed in an alkenone-sea surface temperature (SST) record at the ODP 1233 site near the Chilean coast[16], although no further slope changes corresponding to AIM1 or ACR are shown. Conversely, the alkenone-SST record from a marine core (MD97-2120) collected in the Southwest Pacific[17] shows an uninterrupted deglacial warming comparable to EDC–TALDICE records (Fig. 3). Therefore, both marine and ice core sequences depict a different rate of warming in the South Chilean coast/South Atlantic compared with the Indo/South Pacific, starting around 16 kyr BP. The warming slowdown at EDML–DF is synchronous with the deceleration of the CO_2 rise[18], with the unusually high $^{231}Pa/^{230}Th$ ratio in abyssal North Atlantic sediments interpreted as a weaker Atlantic meridional overturning circulation strength[19], with minimum $\delta^{18}O$ values at NGRIP (Fig. 2) and with distinct change in the strength of the Asian monsoon[20]. Specific changes in the Atlantic sector linked with atmospheric circulation (westerly wind position), winter sea-ice extension and Antarctic Bottom Water formation may be involved in the parallel deceleration of the CO_2 rise. Although it is not clearly imprinted in the Atlantic sector (EDML–DF), the culmination of AIM1 is clearly visible in the Indian Ocean sector dated at 14.7 ± 0.3 kyr BP on the TALDICE-1 chronology, 14.5 ± 0.2 kyr BP on the new EDC age scale[8] (Fig. 2). Between 16.0 kyr BP and AIM1, different trends of

moisture-source temperatures are derived from deuterium-excess data[15] at EDML and EDC. Different shifts in moisture sources are probably linked to reorganization of atmospheric circulation at basin scale. A southward displacement of westerly winds has recently been reported[21] during Northern Hemisphere stadials. The different rates of warming between 16.0 kyr BP and AIM1, observed at EDML–DF and EDC–TALDICE, suggest a different expression of the bipolar see-saw in the two regions. The underlying mechanisms will be investigated in future through new observations and modelling studies.

The onset of ACR in TALDICE and EDC chronologies corresponds to the DO1 onset (14.7 kyr BP) in the NGRIP ice core[5] and with the minimum Δ age chronology at LD (ref. 11). The ACR onset also corresponds to the timing of the exceptionally large Melt Water Pulse 1a (MWP1a) inferred from relative sea-level records. MWP1a occurred at around 14.6 kyr BP with a global sea-level rise between 10 and 20 m in a few centuries[22]. Observational data and modelling studies indicate that Antarctica contributed partly to MWP1a (ref. 13). Our new synchronized isotopic records suggest that the ACR could be a response to MWP1a, which in turn may partially originate from Antarctica after a prolonged deglacial warming. EDML and TALDICE are located close to the most important areas of Antarctic deepwater formation. A massive freshwater release in the high-latitude Southern Ocean is expected to shut down convection, reduce southward heat transport and increase sea ice and associated albedo feedbacks, inducing high-latitude Southern Ocean cooling[23]. This effect is still

a subject of debate between modelling groups[7,24], which reinforces the importance of palaeoclimate records as targets of numerical simulations. Our data support the hypothesis that the DO1 (B/A) is due to a sudden Atlantic meridional overturning circulation recovery from the Heinrich 1 event[7] and by a decrease in Antarctic Bottom Water formation in competitive see-saw behaviour with North Atlantic Deep Water[25].

There is now growing evidence that the end of the YD in the North shows the same characteristics of a typical abrupt DO warming event (DO0), associated with the early Antarctic Holocene optimum (AIM0) in a thermal bipolar see-saw pattern[26]. The ACR–AIM0 transition starts synchronously at 12.7–12.9 kyr BP in TALDICE–EDC–EDML (see Supplementary Information), synchronously with the precisely dated glacier retreat in New Zealand[27], demonstrating a coherent picture for the end of deglaciation between mid- and high latitudes of the Southern Hemisphere. The weaker δ^{18}O amplitude of ACR and AIM0 at TALDICE, compared with other EAP ice cores (Fig. 2), can be explained with local elevation and air-mass-trajectory changes (see Supplementary Information).

Located in the Ross Sea sector, TLD is the most remote ice-core site from the North Atlantic 'centre of action', and still clearly shows a thermal bipolar see-saw behaviour during the last deglaciation. This paper highlights the distinct regional climate fingerprint between the Indo-Pacific and the Atlantic sectors between 16.0 kyr BP and AIM1. Understanding and simulating the bipolar and peri-Antarctic sequences and patterns of events and their interplay with the carbon cycle are critical challenges for earth and climate system modelling, although many gaps remain in the description of the past regional Antarctic climate variability.

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Author contributions

B.S., D.B., M. Baumgartner, M. Bonazza, S.F., L.G., V.M-D., B.M., A.S., S.S. and E.S. contributed to new TALDICE δ^{18}O and CH$_4$ measurements. D.B., S.A., E.B., M. Baroni, E. Capron, E. Castellano, B.D., A.L., B.L-D., C.M., M.M., B.N., F.P., J.R.P., C.R., M.S. and R.U. contributed to measurements and modelling used for TALDICE dating and ice flow description. B.S. and M.F. prepared the figures and wrote most of the manuscript with the main contributions of D.B., J.C., B.D., V.M-D., J.J., B.L-D., B.N., J.R.P. and T.F.S. All authors worked on the comparison of the different records and their interpretations.

Additional information