# Antarctic climate signature in the Greenland ice core record

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**A numerical algorithm is applied to the Greenland Ice Sheet Project 2 (GISP2) dust record from Greenland to remove the abrupt changes in dust flux associated with the Dansgaard–Oeschger (D–O) oscillations of the last glacial period. The procedure is based on the assumption that the rapid changes in dust are associated with large-scale changes in atmospheric transport and implies that D–O oscillations (in terms of their atmospheric imprint) are more symmetric in form than can be inferred from Greenland temperature records. After removal of the abrupt shifts the residual, dejumped dust record is found to match Antarctic climate variability with a temporal lag of several hundred years. It is argued that such variability may reflect changes in the source region of Greenland dust (thought to be the deserts of eastern Asia). Other records from this region and more globally also reveal Antarctic-style variability and suggest that this signal is globally pervasive. This provides the potential basis for suggesting a more important role for gradual changes in triggering more abrupt transitions in the climate system.**

Dansgaard–Oeschger events | rapid climate change | GISP2 dust record

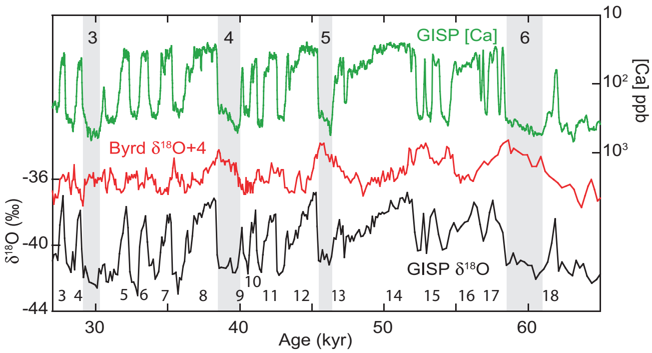


**Fig. 1.** Relations between dustiness over Greenland (represented by [Ca] from the GISP2 ice-core; ref. 31) and temperature variability in Antarctica (7) and Greenland (54) during the last glacial period (all records are temporally aligned using methane correlation; ref. 36). Upper numbers denote Heinrich events, and lower numbers denote canonical D–O events (2). Changes in Greenland dust during Heinrich stadials tend to resemble Antarctic temperature variability.

The discovery of repeated, abrupt, high-amplitude shifts in Northern Hemisphere climate during the last glacial period (e.g., refs. 1 and 2) has provided a major stimulus for paleoclimate research and fuelled debate over the possible nature of future climate change. The millennial-scale Dansgaard–Oeschger (D–O) oscillations, first observed in temperature records from Greenland ice cores, are characterized by the repeated asymmetric alternation between cold (stadial) and warmer (interstadial) conditions (Fig. 1). The transition from stadial to interstadial state is typically abrupt (>10°C temperature rise within a few decades) and is followed by more gradual (century-scale) interstadial cooling before a final transition back to stadial conditions. The close correspondence between temperature variations across the North Atlantic (3–5) and over Greenland leads to the argument for a direct physical connection between D–O variability and the mode of ocean circulation within the Atlantic basin (6). In contrast to that observed in Greenland, glacial age temperature variability recorded by Antarctic ice cores is characterized by a more gradual and symmetric behavior that is approximately out-of-phase with the high-latitude northern hemisphere (7) (Fig. 1). This relationship provides the basis for the so-called bipolar seesaw hypothesis (8, 9) whereby changes in ocean circulation associated with cooling (warming) across the North Atlantic and Greenland drive a corresponding warming (cooling) across the Southern Ocean and Antarctica. However, the precise link between northern and southern ice-core temperature records has proven controversial (10–13). More recently a direct relationship between the amplitude of warming in Antarctica and the duration of northern stadial events has been demonstrated (14), providing clear evidence of a link between the northern and southern high latitudes on millennial time scales.

The observation of D–O type climate variability during Marine Isotope Stage (MIS) 3 [≈60–30 thousand years (kyr) ago] is not confined to Greenland but has been reported from several far-field locations including the North East Pacific (15), the Arabian Sea (16), China (17), and the West Equatorial Pacific (WEP) (18). However, there is increasing evidence that "Antarctic-style" climate variability may have been globally pervasive during the last glacial period (19–23). In particular, atmospheric $CO_2$ variability during MIS 3 (as well as on orbital time scales) appears to be intimately related to regional changes around Antarctica and the Southern Ocean (24–26). Here we demonstrate that a previously unrecognized Antarctic-style signal within the dust record from the Greenland Ice Sheet Project 2 (GISP2) ice core in Greenland provides further evidence for a direct link between these bipolar climate archives and highlights the global influence of Antarctic-style climate variability during the last glacial period.

## Greenland Dust as an Indicator of Global Climate

Ice cores from both polar regions demonstrate that the Earth's atmosphere was significantly dustier during glacial times relative to the modern (27, 28). Furthermore, high-resolution chemical records from Greenland ice cores reveal a strong link between dust loading over Greenland and D–O temperature variability, with stadials being more dusty than interstadial periods (28, 29) (Fig. 1). Dust records obtained from ice cores must be considered as a composite signal containing information about the

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Abbreviations: D–O, Dansgaard–Oeschger; MIS, Marine Isotope Stage; kyr, thousand years; GISP2, Greenland Ice Sheet Project 2; DD, dejumped dust; WEP, West Equatorial Pacific.

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supply of dust in the source region, its uplift to the high (several km) atmosphere and subsequent transport to the polar regions (29). Previous studies have gone some way toward differentiating between the relative importance of these factors (28–30), but explicit deconvolution between variations in source and transport is not straightforward. Mayewski *et al.* (28) used an empirical orthogonal function decomposition of the GISP2 chemical data to define the "Polar Circulation Index" (PCI), able to explain 92% of the total variance of six chemical species over the last 41 kyr. Although the PCI is used to describe changes in large-scale atmospheric circulation, it implicitly includes variations in dust source extent and availability. Ditlevsen and Marsh (30) divided the GISP2 [Ca] record (31) into fast and slow components (distinguished by frequencies above and below $f = 1/200\ yr^{-1}$) and further divided the slow component into three dominant source vectors: continental, oceanic and biochemical. However, the authors state that these vectors include both source area and transport effects. Fuhrer *et al.* (29) suggested that the large and rapid stadial–interstadial jumps were superimposed on a longer-term trend that reflected global climate variability (e.g., global ice volume).

We develop this idea by starting with the basic premise that changes in the atmospheric circulation responsible for transporting dust to Greenland (e.g., the westerly jet stream; refs. 29 and 32) might be expected to share more variability with regional conditions over Greenland (i.e., D–O type variability) than might changes within the source area (in this case eastern Asia; refs. 33 and 34). This may be contrasted with those studies that start by assuming that the large-scale D–O jumps directly reflect source region variability (e.g., ref. 35). We suggest that on millennial time scales the large D–O type jumps are superimposed on a background variability that reflects changes in the source region; the abrupt shifts are then telling us whether or not dust is focused toward Greenland. Removal of the abrupt D–O shifts by "defocusing" the raw dust record (see below) would then allow recognition of the background changes in dust supply. Our argument stems from the visual observation that variations occurring before certain stadial–interstadial transitions in the GISP2 dust record appear to resemble Antarctic temperature variability (Fig. 1). Specifically, throughout stadial periods that contain Heinrich events, the level of dust tends to decrease continuously until the abrupt decrease associated with interstadial warming. Heinrich events tend to be associated with prolonged periods of warming in Antarctica, which themselves are thought to be directly related to the extended duration of cold conditions over Greenland through the bipolar seesaw mechanism (14). Indeed, the clearest evidence for decreasing stadial dust is seen during periods of significant warming in Antarctica. The resemblance of "non-D–O type" dust variability to Antarctic temperature (which is essentially inversely related to Greenland temperature) is used here as the basis for arguing that this mode of variation is likely to originate from outside of Greenland.

## Deconvolution of the GISP2 Dust Record

Isolating the underlying source variability within the GISP2 dust record, as described above, requires the identification and removal of the rapid jumps associated with D–O transitions. To this end, we developed a numerical algorithm to pick D–O transitions based on the rapidity of changes in dust loading through time. Picking D–O transitions using the Greenland dust record has the advantage over use of the temperature record thanks to the generally more obvious (large and rapid) transitions from interstadial to stadial as well as from stadial to interstadial state. By our method all canonical D–O events (2) are identified in addition to a few others that tend to represent incomplete transitions between states [see supporting information (SI) *Text* and SI Fig. 5]. The algorithm generates a "defocusing function," based on each individual D–O transition, which is then combined with the dust record to produce a DD record

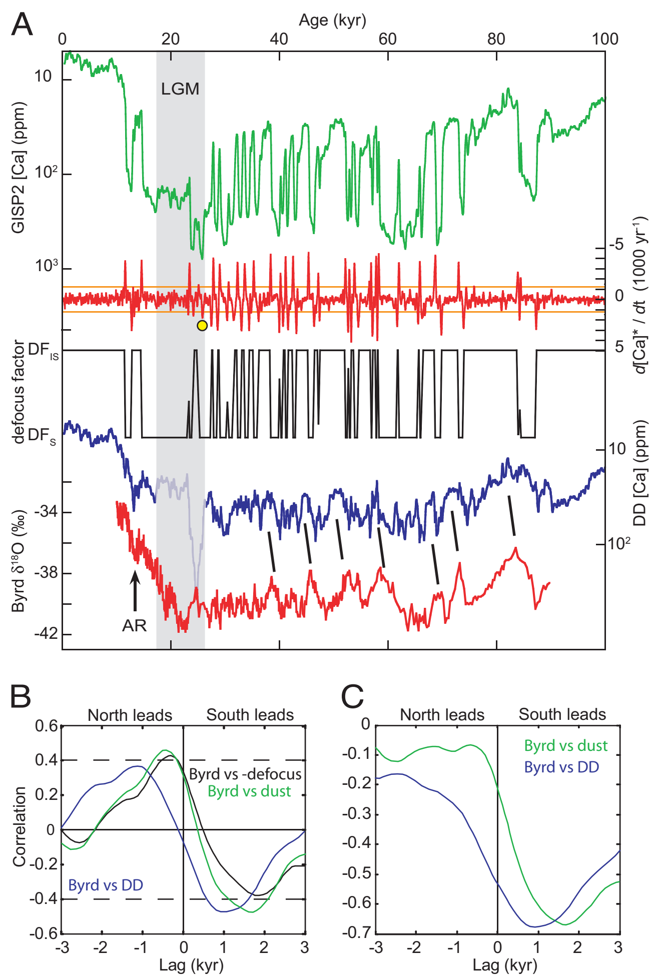


**Fig. 2.** Dejumping the GISP2 dust record. (*A*) From top to bottom are: GISP2 [Ca] record (31), first time differential of $\log_{10}$ [Ca] ($d$[Ca]*/$dt$) with upper and lower limits (±1.15, SD) for picking D–O transitions in orange (yellow circle within the last glacial maximum (LGM) represents the second of two consecutive abrupt increases in dust; see *SI Text*), defocusing function ($DF_{is}$ and $DF_s$ are the interstadial and stadial values, respectively, *SI Text*), the DD record and Byrd $\delta^{18}O$ (36). AR is the Antarctic reversal. (*B*) Lead/lag correlations of the raw and DD records and the defocusing factor versus Antarctic temperature for the interval 85–30 kyr ago after removal of orbital-scale variability (records are hi-pass filtered at 7,000 yr and lo-pass smoothed at 200 yr; see *SI Text*). The DD record shows similar maximum correlative power to the unprocessed record but is shifted in time with maximum correlation attained when southern temperature leads DD by up to 1,000 yr. (*C*) Same as *B* but without high-pass filtering.

(Fig. 2). The defocusing function is similar to a trapezoidal wave form, alternating between two states; interstadial and stadial. When combined with the dust record the function acts to scale stadial dust values by a constant factor (<1) to align them with the interstadial portions of the record. The procedure therefore implies that stadial states were anomalously dusty (the specific defocusing factor used for stadial periods is set to achieve maximum contiguity of the resulting dejumped record). Only two focusing states are defined to maintain simplicity, although this may be too simplistic for the last glacial maximum (LGM) interval when the magnitude and direction of abrupt shifts appears less uniformed than for other intervals (see *SI Text*). For this reason, the LGM is omitted from further discussion. The procedure also implies that the atmospheric expression of D–O oscillations in Greenland ice cores is quite symmetric (i.e., with similar transitions in both directions) and perhaps not as asym-

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metric as might be inferred from the Greenland temperature records.

After applying the defocusing routine to the GISP2 [Ca] record (31), a visual similarity between the DD record and Antarctic temperature variability is apparent (Fig. 2). In addition to the general increase in dustiness during the glacial period, millennial-scale decreases in DD tend to correspond to Antarctic warming events, whereas the deglacial Antarctic cold reversal is apparently aligned with a transient maximum in the DD record. This observation begs the question: Does climatic variability in the source region of Greenland dust contain an Antarctic-type signature and hence suggest a more global nature of this signal?

Also apparent in Fig. 2 is a temporal lag of the DD record behind Antarctic temperature during the glacial period (≈85–30 kyr ago). A lead/lag analysis of the raw and DD records with Antarctic temperature over the interval 85–30 kyr ago (after filtering out orbital-scale variability below $f = 1/7{,}000$ yr) reveals that the ≈500 year positive lead of northern dust over southern temperature (equivalent to the anticorrelation between the respective temperature records; ref. 10) is not present in the DD record (Fig. 2*B*). This is a direct effect of removing the abrupt D–O transitions, as illustrated by the presence of the same lag between the defocusing function and Antarctic temperature. Therefore, the DD record is not a damped version of the raw dust record; rather, it is phase shifted and shows strongest (negative) correlation with Antarctic temperature with a lag of several hundred years behind the southern signal. This lag is also seen for the same records without orbital filtering (Fig. 2*C*) (all records are temporally aligned by methane correlation; ref. 36). Although dejumping the dust record alters the phasing between northern and southern records, it does not improve the correlative power between the records. To test the hypothesis that climatic variability in the source region more closely matches Antarctic variability than it does Greenland it is necessary to evaluate other records from this region and beyond.

## Globally Pervasive Antarctic Climate Signal

Dust arriving at Greenland today and during the last glacial period is believed to originate in the deserts of eastern Asia (33, 34). This is thought to be independent of changes between periods of high and low dust flux, at least during MIS 2 (34). If the DD record describes changes in source region climate we may expect to find similar variability in other climate sensitive proxies from the same region. A high resolution speleothem record from Hulu cave in China (17) provides one such example (Fig. 3). This record is thought to reflect changes in the intensity of the East Asian Monsoon and has previously been compared with the temperature record from Greenland. The East Asian Monsoon originates in the WEP, the warmest part of the modern ocean and an important component of the global climate system. A high-resolution record of changing surface-ocean hydrographic conditions from this region during MIS 3 (18) has also been correlated with conditions over Greenland (Fig. 3). However, recent results from the East Equatorial Pacific show no clear evidence for a North Atlantic climate imprint in this region, at least at the millennial scale, and further show that climate variability during MIS 3 displayed somewhat similar behavior to Antarctic temperature variability (19). In light of this finding, we reanalyzed the Hulu Cave and WEP data.

From a visual inspection of the WEP and Hulu Cave records it is not immediately apparent that they should be aligned with Greenland temperature in preference to Antarctic climate variability (see *SI Text* for details of age models). When placed on a linear age model, the WEP record seems to resemble records from Antarctica more closely than it does that from Greenland. This is highlighted by a lead/lag analysis between the various records (Fig. 3 *B* and *C*). For the interval, 60–30 kyr ago (most relevant for D–O variability), the WEP record correlates significantly better with records from Antarctica. However, we do not advocate tuning the WEP record to either Greenland or Antarctica because this immediately implies some sort of mechanistic relationship that cannot be inferred from a similarity in appearance between the records. Nevertheless, our analysis suggests that the WEP record does contain an Antarctic-style climate signal.

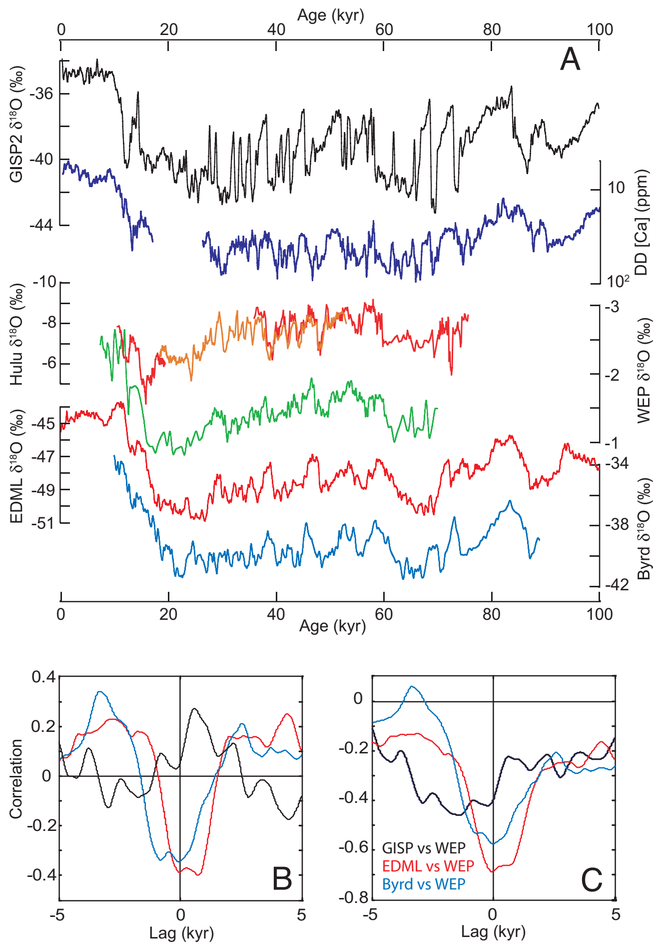


**Fig. 3.** Comparison between regional climate records. (*A*) From top to bottom: $\delta^{18}O$ from GISP2 (54), the dejumped GISP2 dust record (both on the GISP2 time scale; ref. 55), $\delta^{18}O$ from Hulu Cave, China (17) (absolutely dated U/Th time scale), planktonic $\delta^{18}O$ from the WEP (18) (linear sedimentation rate; see *SI Text* and SI Fig. 6), Antarctic $\delta^{18}O$ records from Dronning Maud Land (on the EDC3 time scale; ref. 14) and Byrd Station (7) (on the GISP2 time scale). Visually, the Hulu Cave and WEP records seem to share more similarity with the Antarctic records than they do with the Greenland record although the pronounced maxima in the Hulu Cave record correspond to North Atlantic Heinrich events. (*B*) Lead/lag correlations of Greenland and Antarctic temperature records versus the WEP record for the period 60–30 kyr ago (records are hi-pass filtered at 7,000 yr and lo-pass smoothed at 200 yr). The correlations between WEP and Antarctic temperature are superior to that between WEP and Greenland. (*C*) Same as *B*, but including orbital-scale variability.

The case is less clear for the Hulu Cave record. Although a lead/lag analysis again suggests better correlation between the Hulu record and Antarctic variability than with Greenland (*SI Text* and SI Fig. 7), the precise absolute dating of the speleothem record confirms that North Atlantic Heinrich events are reflected by extreme maxima in speleothem $\delta^{18}O$ (interpreted as a weakening of the summer East Asian Monsoon) (17). Indeed, the effects of a pronounced reduction in the Atlantic Meridional Overturning Circulation (AMOC) (as thought to be associated with Heinrich events; ref. 37) are predicted to be global in extent

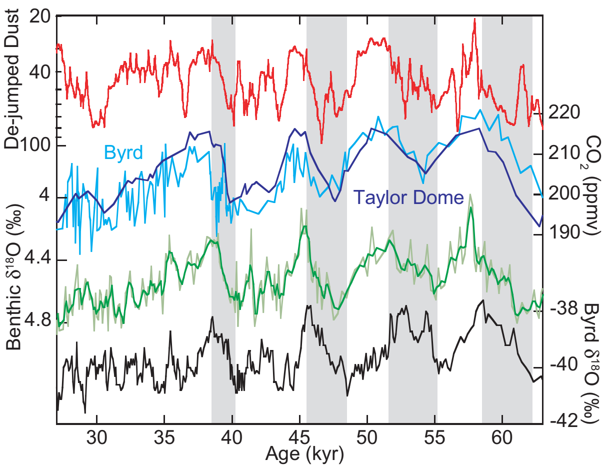


**Fig. 4.** The DD record as compared with atmospheric $CO_2$ [from the Byrd (25) and Taylor Dome (24) ice cores], deep Atlantic benthic foraminiferal $\delta^{18}O$ (plus 3-point running mean) (5) and Antarctic temperature (7). All records are on the GISP2 time scale. The two records of $CO_2$ have been detrended by subtraction of a linear decrease of 0.3 ppmv/kyr centered on 45 kyr ago. Shaded gray areas loosely define warming periods in Antarctica. The DD, $CO_2$, and benthic $\delta^{18}O$ records all display apparent time delays behind the Antarctic record. See also *SI Text* and SI Fig. 8.

(e.g., ref. 38). These effects include reduced precipitation over large parts of the northern hemisphere and increased rainfall in South America and Africa caused by a southward shift in the Intertropical Convergence Zone (38). However, although the near-instantaneous effects of Heinrich AMOC collapses may be global, this does not necessarily imply that all D–O events should be expected to have the same influence. It is clear that Heinrich stadial events should be considered distinct from "regular" D–O stadials, as evidenced by a range of oceanic proxies (e.g., refs. 3 and 39–41). Further evidence from Brazilian speleothems also suggests that southward migration of the ITCZ during MIS 3 was particularly pronounced only during Heinrich events, highlighting the anomalous conditions during these periods. We argue that records such as that from Hulu Cave may well be expected to show a composite signal comprising the effects of near-instantaneous shifts in atmospheric circulation superimposed on a background variability that we contend reflects Antarctic-style climate fluctuations. This argument is based on the observation of the Antarctic signal in influential regions such as the tropical Pacific as well as its appearance in the DD record.

A question may then be raised concerning the DD record; should this not also reflect Heinrich events? In fact, the record does show maxima (perhaps corresponding to the dry conditions associated with a weakened monsoon) during Heinrich stadials. This directly reflects the fact that the highest values in the raw dust record occur during these intervals (Fig. 1). This observation in itself may be used to argue for a relationship between the Hulu Cave monsoon record and the Greenland dust record that is not shared by the Greenland temperature record; namely that Heinrich events (which are reflected by extrema in both Greenland dust and Hulu $\delta^{18}O$) are not marked by "extremely" cold conditions over Greenland (42). If records such as that from Hulu Cave and the surrounding region do contain signals of multiple origin (notably D–O type variability superimposed upon an Antarctic-style modulation) it is possible that the deconvolution method applied here may obscure D–O type variability associated with the source region as well as that associated with transport to Greenland. Future work is required to better constrain the individual components of climate signals from this region and more generally.

## Global Transmission of the Antarctic Signal

The observation of Antarctic-style climate variability in proxy records from remote settings such as the tropical Pacific and its appearance in the record of dust accumulation in Greenland suggest that this climate signal is more pervasive than perhaps previously assumed. An immediate question is then what enables the global transmission of such a signal? In fact, "time-delayed" variants of an "Antarctic-style" climate signal may be found elsewhere. For example, the close correspondence between Antarctic temperature and atmospheric $CO_2$ is well established for various time scales over the last 650 kyr (e.g., ref. 26) including the millennial scale variability observed in Antarctica during MIS 3 (24, 25). This correspondence highlights the important role of the Southern Ocean for atmospheric $CO_2$ variability. Of particular relevance here is an apparent time lag of $CO_2$ behind Antarctic temperature. Several studies have attempted to quantify the precise phase relationship between these key variables. Those focusing on glacial terminations have identified lags of 600 ± 400 yr (43), 800 ± 200 yr (44), and 800 ± 600 yr (45), whereas a detailed statistical analysis of the last 420 kyr yielded an estimate of 1,300 ± 1,000 yr (46). Two studies of $CO_2$ variability during MIS 3 provide estimates of 1200 ± 700 yr (24) and 720 ± 370 yr (25) for the lag of $CO_2$ behind temperature during this interval. This is similar to the observed lag of our DD record behind Antarctic temperature as highlighted by the close temporal correspondence between $CO_2$ and the dejumped record when plotted on a common time scale (Fig. 4). The fact that changes in atmospheric $CO_2$ lag behind Antarctic temperature variations does not diminish the potential role of $CO_2$ as a driver of climate change.

On the other hand it may be argued that $CO_2$ variations of 10–20 ppmv, as observed during MIS 3, might not have been sufficient to drive climatic changes such as those implied by the DD record. The oceans represent a potential alternative medium for transmission of the Antarctic signal (quite beyond the fact that they may also represent the origin of this signal) because changes in $CO_2$ themselves are likely to be driven by oceanic processes. We have mentioned the observation of an Antarctic-style signal from several marine settings including the influential tropical surface Pacific. However, as yet there is no way to tune these records to investigate the precise temporal relationship between them and the high southern latitudes. This represents an important step that should be tackled in the near future. One marine record that can be tuned to ice-core records with sufficient precision to address this issue is from core MD95-2042, taken at 3,146 m on the Iberian margin (5). Shackleton *et al.* (5) demonstrated that the benthic oxygen isotope record from this core resembles Antarctic temperature variability when placed on the ice-core time scale by tuning of the planktonic isotope record to Greenland. This tuning exercise permits us to identify a variable phase lag of up to several hundred years between Antarctic temperature and the deep Atlantic benthic $\delta^{18}O$ record (Fig. 4 and *SI Text*). Although we cannot assess here the individual components that comprise the benthic $\delta^{18}O$ signal (i.e., the temperature and oxygen isotopic composition of seawater including ice volume effects), it is clear that oceanic processes do act to transmit an Antarctic-style signal with a finite lag behind the ice-core temperature record.

The D–O oscillations provide the most dramatic example of abrupt climate variability during the last glacial cycle. The underlying cause of these abrupt climate shifts has yet to be resolved but changes in North Atlantic sea ice cover are thought to play a crucial role in the associated temperature changes over Greenland (47, 48). Abrupt changes in sea ice cover must be driven by changes in other parts of the climate system (48), which may themselves be more gradual in nature. For example changes in ocean circulation, which might be either local (49, 50) or more distal in origin (such as the southern high latitudes; ref. 51), could provide the trigger for an abrupt sea ice retreat in the North Atlantic (48). Changes in surface wind stress in the North Atlantic may represent an alternative trigger (52). Such changes might also have nonlocal origins; e.g., the interaction of atmospheric circulation with land-based ice sheets or changes in the tropical ocean-atmosphere system (48, 53). The one-to-one coupling between millennial-scale temperature variations in the high northern and southern latitudes (14) provides evidence for an oceanic role in the global manifestation of D–O variability (i.e., the bipolar seesaw). Our findings suggest the more global expression of a time-delayed "Antarctic-style" climate signal that may be the product of Antarctic temperature variability itself or the oceanic mechanism that controls it. By extension, it may be argued that an analogous (although not necessarily identical) time-delayed Antarctic-style climate signal may be capable of providing a trigger for the rapid climate shifts recorded in Greenland and the North Atlantic region during MIS 3, thereby representing a potential feedback on northern glacial climate variability.

## Conclusions

A numerical algorithm was developed for the identification of rapid shifts in the Greenland dust record associated with the D–O transitions of the last glacial period and their removal to reveal millennial-scale variations in the source region. The algorithm relies on the similarly abrupt changes in dust accumulation during interstadial-to-stadial and stadial-to-interstadial transitions and implies that the D–O oscillations (at least in terms of their atmospheric imprint) were rather more symmetric in form than can be inferred from Greenland temperature records. Deconvolution of the Greenland dust record by removal of the abrupt D–O jumps reveals a previously unrecognized variability that is reminiscent of Antarctic temperature fluctuations. Such variability is likely to reflect changes in the deserts of eastern Asian, the source region for Greenland dust. Similar variability in records from the surrounding region strengthens the contention that changes in the East Asian Monsoon system may also share variability in common with Antarctica. Furthermore, the global effects of Heinrich stadial events would be expected to overprint this background variability, giving rise to complex signals of multiple origin. Evidence for the physical expression of an Antarctic-style climate signal in a remote location demonstrates the global significance of this signal characteristic and provides a potential basis for suggesting a more important role for gradual changes in triggering more abrupt transitions in the climate system.

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