Ice cores record significant 1940s Antarctic warmth related to tropical climate variability

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Although the 20th Century warming of global climate is well known, climate change in the high-latitude Southern Hemisphere (SH), especially in the first half of the century, remains poorly documented. We present a composite of water stable isotope data from high-resolution ice cores from the West Antarctic Ice Sheet. This record, representative of West Antarctic surface temperature, shows extreme positive anomalies in the 1936–45 decade that are significant in the context of the background 20th Century warming trend. We interpret these anomalies—previously undocumented in the high-latitude SH—as indicative of strong teleconnections in part driven by the major 1939–42 El Niño. These anomalies are coherent with tropical sea-surface temperature, mean SH air temperature, and North Pacific sea-level pressure, underscoring the sensitivity of West Antarctica's climate, and potentially its ice sheet, to large-scale changes in the global climate.

Antarctica | climate change | El Niño

A large void in meteorological observations has complicated the understanding of climate variability and the detection of climate change over the West Antarctic Ice Sheet (WAIS) and the adjacent South Pacific Ocean. Climate change in West Antarctica is of particular interest because climate-driven changes in the mass balance of the WAIS could either mitigate or make substantial contributions to global sea-level rise (1). Although analyses of data from satellite-based sensors (2–4) and climate field reconstructions based on sparse instrumental observations (refs. 5 and 6 and E.J.S., D.P.S., S. D. Rutherford, M. E. Mann, J. C. Comisa, and D. T. Shindell[§]) have helped to resolve climate trends and patterns during recent decades, several key questions remain unanswered. For example, it has been difficult to place Antarctic temperature trends in the context of global-scale, anthropogenically-driven warming (7) and to characterize the association of Antarctic climate with the El-Niño–Southern Oscillation (8).

Ice cores are among the only sources of longer climate records from the Antarctic and are therefore essential for assessing climate change there. Here, we present ice core evidence that links 20th Century West Antarctic climate variability to the tropics and the mean warming of the Southern Hemisphere (SH). Our approach is to average several high-resolution stable isotope records to reduce local meteorological noise and to identify anomalies of large-scale significance (9, 10). This is achieved for West Antarctica with the availability of several records from the International TransAntarctic Scientific Expedition, combined with three records from earlier drilling projects (Table 1).

The interpretation of stable isotope ice core records has recently been clarified by modeling studies. In the Antarctic, isotopic composition is fundamentally coupled to the large-scale transport of moisture, heat, and mass among the tropics, mid-latitudes, and the ice sheet (11, 12). Physical isotope models show that polar temperature and isotopic composition depend on the strength of the eddy-driven zonally symmetric circulation and, as such, isotopic composition on the ice sheet reflects polar temperature under a range of circulation regimes (11). Poleward heat and moisture transport to the Antarctic continent is not zonally uniform; it is greatest in the West Antarctic over the Ross, Amundsen, and Bellingshausen Seas and is strongly modulated by low-level synoptic activity (13). Therefore, West Antarctic ice core records are particularly sensitive indicators of circulation-driven changes in the polar climate. Our eight records are restricted to the Pacific sector (60W–180W), and should reflect anomalies of common sign with respect to the Southern Annular Mode and El Niño-related teleconnection patterns (4), assuming that the spatial patterns from observations hold through time. A study of five Antarctic-wide high-resolution ice cores showed evidence that the most prominent pattern in temperature variability, with negative anomalies in the Peninsula region and positive anomalies over the bulk of the continent, and vice versa, has been present throughout the 20th Century (14).

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Results and Discussion

Our composite of eight ice core records (Fig. 1) is significantly correlated with annual mean 2-m temperatures from the ERA-40 Reanalysis averaged over the WAIS ($r = 0.71$, $P < 0.01$, linearly detrended) for 1980–1999, the overlap period with the most reliable reanalysis data (15). It is also in good agreement with the statistically reconstructed West Antarctic mean surface temperature of Steig and others,[§] sampled at the grid boxes of the ice core sites, for the period of overlap, 1957–1999 ($r = 0.46$, $P < 0.01$, linearly detrended). Trends in the ice core time series, the statistical reconstructions and observations are consistent in sign, indicating annual mean warming over West Antarctica during the last 50 years (refs. 2 and 5 and Steig *et al.*[§]).

A remarkable feature of the ice core records is the exceptionally large amplitude of anomalies that occurs ≈1940. The large shift from major positive anomalies in 1940–41 to negative anomalies in 1943 is obvious in the composite record and remarkably consistent among the individual records (Table 2). The range in annual $\delta^{18}O$ is 3–4‰, which implies mean temperature swings from 1941 to 1943 of up to ≈5 C by using a model-based scaling (11), or ≈7.5 C by using variance scaling to the ERA-40 west Antarctic instrumental record. Not all of the variance can be unequivocally attributed to local temperature, as the ice core record also reflects circulation and nonlocal influences that can somewhat alter the scaling relationship.

A hypothesis for the 1939–43 interval has been presented to explain Northern Hemisphere (NH) climate anomalies, including extreme winter cold in Europe, warmth in southern Alaska, and high ozone concentration over the entire NH (16). These anomalies may be linked to a strong El Niño event that was

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Table 1. Summary information for ice core sites

Site name	Lat, °N	Long, °E	Elevation, m	Type	End year
Dyer Plateau	−70.66	−64.5	2,002	$\delta^{18}O$	1989
Siple Station	−75.92	−84.15	1,054	$\delta^{18}O$	1983
01–5 ITASE	−77.06	−89.14	1,239	$\delta^{18}O$	1999
00–5 ITASE	−77.68	−123.99	1,828	δD	1999
01–2 ITASE	−77.84	−102.91	1,336	$\delta^{18}O$	1999
01–3 ITASE	−78.12	−95.65	1,620	δD	1999
00–1 ITASE	−79.38	−111.23	1,791	δD	1999
Siple Dome A core	−81.65	−148.81	615	δD	1993

References and data sources are given in *Materials and Methods*.

unusual in its persistence. Tropical Pacific SST and rainfall anomalies indicate that this El Niño appeared in the boreal autumn of 1939 and lasted until the boreal spring of 1942, making it the only large event of the past century that lasted for 3 years (16, 17). We suggest, based on our ice core evidence, that this event had an exceptionally strong influence on the South Pacific and West Antarctic region.

Not all El Niño events are associated with strong Antarctic anomalies, but comprehensive reviews have shown that they have an important influence on high-latitude climate variability (8, 18). In general, El Niños are associated with a blocking high in the southwest Pacific (≈120 W, 65S), a cyclonic anomaly in the southwest Atlantic (0–60W), increased poleward heat and moisture transport over the West Antarctic, positive temperature and snowfall anomalies in the Ross Sea and inland over our region of core sites, and negative temperature and precipitation anomalies in the Weddell Sea and the continental region adjacent to the Atlantic.

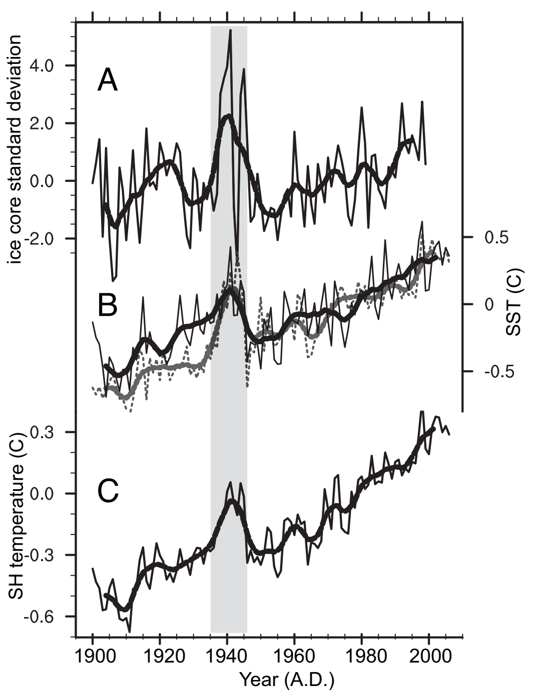

Fig. 1. The West Antarctic ice core composite record compared with SST and hemispheric mean surface air temperature for 1900–1999. (*A*) Time series of the annual mean and 5-year smoothed standardized ice core composite compared with *B*, observed JJA SST records for 20S-20N (dark solid lines) and 20S-60S (light dashed lines). (*C*) Also shown is the annual SH mean temperature record. The light-gray shading highlights the warm 1936–45 decade. The SH temperature record (37) and the Hadley SST2 dataset (21) were obtained from the web site of the Climatic Research Unit, University of East Anglia (Norwich, U.K.).

To illustrate the 1939–42 event and its Antarctic connection, we use reconstructed sea-level pressure (SLP) (19) and sea surface temperature (SST) fields (20) (Fig. 2), zonal-mean SST (21) (Figs. 1 and 3), the Niño 3.4 SST index (Fig. 3) (22), central equatorial Pacific rainfall from rain gauge stations (17) (Fig. 3), and the North Pacific SLP index (NPI) (Fig. 3) (23). The SLP data are poorly constrained at high southern latitudes (19), so the anomalies shown are not definitive. However, the different data types compliment each other. The equatorial SST data are better constrained by observations, and the rainfall data are taken directly from station gauge measurements.

The SST and SLP data show a distinctive El Niño pattern at the peak of the event recorded in the ice cores in 1940–41 (Fig. 2). There is a very strong high centered near the West Antarctic coast and positive SLP anomalies over the entire Antarctic continent. Studies of recent El Niños and their high-latitude response suggest that the location of large positive SST anomalies over the dateline is favorable for driving deep convection and generating Rossby wave trains propagating to the Amundsen–Bellinghausen Seas (24). The anomalous forcing of Rossby waves is further implied by the copious amount of rainfall in the Niño4 region in 1940–42 (Fig. 3), a signature of deep convection. The boreal winter SLP anomaly field of 1940–41 displays a strongly teleconnected atmosphere with the characteristic El Niño associations: negative phase Southern Oscillation, deep Aleutian Low, negative North Atlantic Oscillation/Northern Annular Mode, negative Southern Annular Mode, and high off of West Antarctica. Thus, the available data display the signature of a major El Niño event and, particularly, an event that was associated with a strong atmospheric circulation response in the Antarctic.

We interpret the positive isotopic anomalies during the El Niño event as indicative of the atmospheric circulation response at high southern latitudes forced by tropical deep convection, rather than as a shift in the location of the moisture source of Antarctic precipitation. The circulation anomalies are indicative of an equatorward storm track and weakened midlatitude eddy circulation. In light of a new isotope modeling study (11), this regime is associated with less isotopic depletion. Indeed, a circulation regime leading to isotopic enrichment and decreased polar temperature is highly unlikely, because the strength of the meridional temperature gradient is inextricably linked to the strength of the circulation (11). The positive sea level pressure anomalies in the South Pacific and the equatorward storm track are characteristic features of most El Niño events (8, 18). The apparent unusual strength of the circulation anomalies and the isotopic response may be linked to the phasing with the Southern Annular Mode (25).

Fig. 3 displays the annual ice core data and monthly resolution observations for the 1930s and 1940s. The timing of isotopic anomalies, which peak in 1941 and abruptly transition in 1942,

Table 2. The difference of the years 1941 (the height of the El Niño) and 1943 (the height of the La Niña) at each ice core site

Core	ITASE 00–1	ITASE 00–5	ITASE 01–3	ITASE 01–5	ITASE 01–2	Siple Station	Siple Dome	Dyer Plateau
1941–1943, SD	3.49	1.88	4.55	5.04	−2.96	3.96	3.09	2.67
1941–1943, ‰	3.20 ($\delta^{18}O$)	16.89 (δD)	30.87 (δD)	4.83 ($\delta^{18}O$)	−3.25 ($\delta^{18}O$)	2.58 ($\delta^{18}O$)	31.4 (δD)	2.24 ($\delta^{18}O$)

Values are in units of standard deviations from the 1961–1990 climatology and absolute per mil (‰) values, except at sites with end years before 1990; at these sites the climatology is calculated from 1961 to the end year.

is consistent with the peak and end of the El Niño, as highlighted in all of the observations and indicated by the Niño3.4 index. The tropical SST anomalies persist throughout the boreal summers of 1940 and 1941, likely resulting in a teleconnection in the winter SH and the West Antarctic, as supported by studies of modern data linking tropical outgoing longwave radiation anomalies to the leading modes of wintertime SH high-latitude circulation variability (24, 26). A tropical origin of the anomalies in the Antarctic ice core record is further implied by the similarity of the ice core record and the NPI. The NPI records the intensity of the Aleutian Low, which is known to strongly respond to tropical variability (27). After the multiyear El Niño, La Niña conditions occurred for one season, from late 1942 to early 1943, and this anomaly is reflected in all of the Pacific records. Less clear are the origins of the strong positive anomalies in 1944–45 seen in the ice core record, the NPI, and tropical SST, and the rapid cooling in late 1945 that is evident in the tropical and midlatitude SST anomalies as well as the ice core record (Figs. 1 and 3). The warming may partially reflect a recovery from La Niña conditions to near neutral conditions, yet ENSO activity cannot explain the magnitude of the positive anomalies in 1944–45 and rapid cooling at the end of 1945. If it was forced from the tropics, the origin of this anomaly may have been in the western tropical Pacific or Indian Ocean, rather than the Niño3.4 region. For the North Pacific connection, this is supported by the analysis of Deser and others (27), who find that a regime shift associated with multidecadal North Pacific and Indian-Pacific tropical variability occurred in 1946, not at the end of the 1939–42 El Niño. The origins of this regime shift, and its possible connections with the warmth of the 1936–45 decade are not

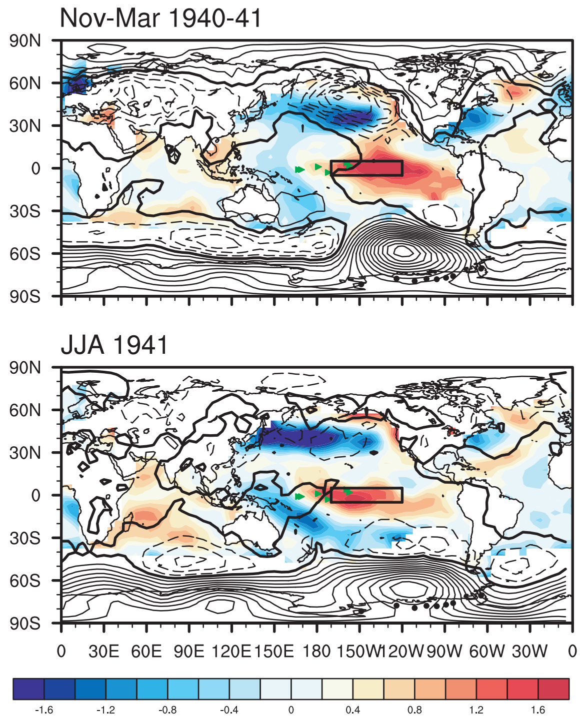

Fig. 2. Maps showing SST anomalies in °C (color scale) and SLP anomalies (contours every 1 hPA, positive anomalies solid lines and negative anomalies as dashed lines) for the peak of the El Niño event in 1940–41. The black dots in West Antarctica indicate the ice core sites. The sites of the rainfall observations are indicated with green triangles, and the Niño3.4 region is outlined by the rectangle. The SST data are from the Kaplan dataset (20). The SLP data are from the Hadley SLP2 dataset (19). Both datasets were obtained from the Earth System Research Laboratory of the National Oceanic and Atmospheric Administration.

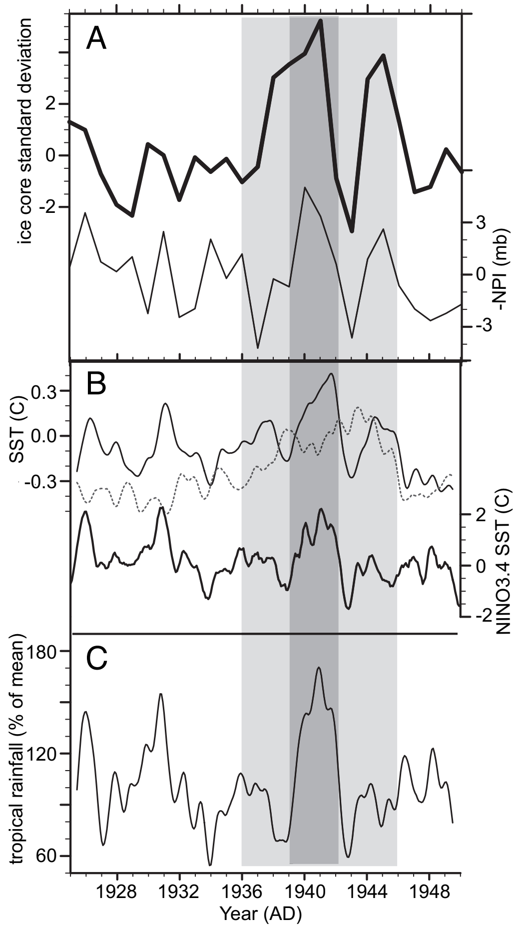

Fig. 3. Time series covering the 1925–1950 period, with the warm 1936–45 decade highlighted by light-gray shading and the 1939–42 El Niño event highlighted by darker-gray shading. (*A*) Annual resolution West Antarctic ice core index (dark line) and the North Pacific Index (light lines) for the November-March season (23). (*B*) Monthly data are shown after smoothing with an eight-point Gaussian filter. Included are zonal mean JJA SST for 20N-20S (light solid line) and for 20S-60S (dotted line) as well as the Niño3.4 SST index (22) (heavy solid line). (*C*) An index of rainfall on central tropical Pacific islands (17). The NPI and Niño3.4 index were obtained from the Climate Analysis Section of the National Center for Atmospheric Research, and the Wright rainfall index was provided by Clara Deser. The SST data are, again, from the HadleySST2 dataset.

Table 3. Value of the correlation coefficient between the Antarctic ice core record and several of the time series shown in Figs. 1 and 3

Parameter	Ice core, annual correlation, 1900–1999	Ice core, correlation after 5-yr smoothing, 1900–1999
Annual SH mean temperature	**0.43**	**0.83**
20N-20S, JJA tropical SST	**0.39**	**0.73**
20S-60S, JJA SST	**0.28**	**0.78**
Annual Niño3.4 SST	0.06	**0.33**
Nov-Mar North Pacific index	**0.34**	**0.50**
Tropical index (27)	**0.24**	**0.45**

The linear trend has been removed before calculation of the correlation. Bold values indicate significance at the 95% confidence level or higher, according to a two-tailed *t* test.

clearly understood. Furthermore, it is an open research question whether tropical and North Pacific interdecadal variability is linked with the Antarctic via the tropics. We find some support for this, as there are significant correlations of the Antarctic record with indices of tropical and North Pacific climate variability (Table 3). A recent study (28) proposes that the cooling in 1945 is (at least in part) an artifact of assimilating different types of measurements into the SST datasets, without making bias corrections. As we noted above, the study (28) also finds that 1945 anomaly is difficult to attribute to a single climatological phenomenon such as El Niño. However, the cooling seen in the isotope record, its correlation with the SST records, and coincidence with anomalies in the NPI, suggests that at least part of this anomaly is real.

A large part of the anomalies ≈1940 are coincident with the 1939–42 El Niño event, yet the Antarctic, SST, and hemispheric-scale records indicate warmth throughout the 1936–45 decade that is not clearly connected with El Niño. The Antarctic 1940s anomalies are coincident with the 1940s warm period that has long been apparent in hemispheric and global mean temperature records (Fig. 1) but has not been interpreted in detail because of the unavailability of gridded climate data at the surface and in the upper atmosphere (16). Previous efforts to understand the warm period have mainly considered the concentration of early 20th Century warming in the high-latitude NH (29–31). Although there are broad similarities between Arctic temperature records and our Antarctic ice core composite, there are also key differences. Peak annual mean temperature anomalies were reached in both polar regions in 1938–1941, yet the Antarctic event started and ended abruptly, whereas the Arctic anomaly evolved more gradually and had greater persistence (30), suggesting different combinations of mechanisms operating in the two regions.

The relative contributions of external forcing and internal climate system variability to early 20th Century warming remain uncertain (29, 32). Notably, 1936–1945 is the only decade of the 20th Century showing observed global mean temperatures outside the 5–95% range of 77 model simulations that included natural only or both natural and anthropogenic forcings (see figure 1 in ref. 33, FAQ 9.2). As ensemble means tend to smooth out the internal variability and emphasize the forced response, it is likely that a substantial amount of internal variability is necessary to explain the anomalies ≈1940.

Averaged over all of Antarctica, ensemble mean model output used for the IPCC AR4 almost invariably depicts large, monotonic warming during the 20th Century rather than the modest warming and large variability indicated by the ice cores and late 20th Century instrumental observations (34). Our ice core record reflects not a simple index of El Niño events, but rather the interaction of large-scale waves originating from the tropics with the high-latitude circulation. On the scale of the Antarctic continent, ice core records are dominated by the Southern Annular Mode (SAM) on the interannual scale yet are in phase with the SH mean temperature at longer time scales (14). Compared with the continental scale record, our West Antarctic ice core record shows a stronger El Niño influence and a larger upward trend over 1900–1999. Based on the variance scaling method, we infer a positive temperature trend of 1.0°C per century. It is not statistically significant, but the magnitude is more similar to the trends in the observed SH mean and model results than is the continental scale record (14, 34). The interaction of the tropical-related variability and the high-latitude (SAM) variability on the interannual scale is superimposed on the longer-term warming trend. Table 3 shows correlations of the ice core record with indices of both tropical and hemispheric-scale variability as support for this wide range of connections. The large variability at high latitudes, combined with the tropical–Antarctic connection, makes data-model comparison challenging, and will need to be addressed in detection–attribution studies. In addition to correctly specifying ozone and greenhouse gas forcing, models must also correctly specify or simulate tropical SST and its response at high latitudes to achieve good simulations of Antarctic climate.

Conclusions

Our ice core evidence suggests that West Antarctic climate variability is strongly linked to the tropics and to the mean warming of the SH. The data indicate that a major Antarctic climate anomaly occurred during the globally warm 1936–45 decade, consistent with the far-reaching influence of the 1939–42 El Niño.

These results help to place Antarctic climate records into the context of global-scale climate variability and change. Previous studies have suggested that variability in El Niño (35) and changes in the circumpolar vortex (36) are driving Antarctic surface temperature trends. However, our results suggest that these mechanisms do not provide complete explanations for Antarctic temperature change over multiple decades. The El Niño connection to West Antarctic climate is intermittent and variable, because it depends on the location and strength of deep convection in the tropics and the interaction of Rossby waves originating from the tropics with the SH zonal flow (8, 24, 25). The warming is not likely associated with high-latitude atmospheric circulation variability alone, because the positive trend in the Southern Annular Mode over recent decades (36) favors cooling at the surface, not warming. The seasonality of the circulation and temperature trends are important in evaluating the causes of climate changes, as shown by the recent spatial reconstructions of surface temperature (refs. 5 and 6 and Steig *et al.*[§]). Seasonal aspects of Antarctic climate change are beyond the scope of this article, although correlations of the ice core record with tropical SST and hemispheric mean temperature suggest, but do not confirm, that SST trends and possibly greenhouse gas increases are affecting Antarctic climate.

Future work will need to address more thoroughly the detection and attribution of Antarctic climate trends. Our present findings offer, first, a longer climate record for Antarctica and, second, insight into large-scale 20th Century climate variability. Taken together, the results underscore the sensitivity of West Antarctica's climate to global climate change, as well as to large-scale variability as exemplified by the 1939–42 El Niño.

Materials and Methods

Ice Cores. Our approach is to average several high-resolution stable isotope records to reduce local meteorological noise and to identify anomalies of large-scale significance (9, 10). At least century-length records are available from eight sites, where annual snow accumulation ranks among the highest in Antarctica, ranging from 11-cm water equivalent to 56-cm water equivalent per year. This permits annual age control and subannual sampling resolution. The overlap of the available records allows the composite record to cover nearly the entire 20th Century, from 1900–1999.

The data include five records from the United States International TransAntarctic Scientific Expedition (ITASE). These records were developed by the authors of this study. The procedures used for obtaining, measuring, and dating these records are discussed in refs. 38–40, and the time series used here are available from the authors and from the World Data Center for Paleoclimatology (Boulder, CO).

We also use the annual mean $\delta^{18}O$ record from Dyer Plateau on the Antarctic Peninsula (41). We obtained the data from R. Mulvaney (personal communication, 2006). We use the annual mean $\delta^{18}O$ record from the Siple Station site in West Antarctica (42). We obtained the data from E. Mosley-Thompson (personal communication, 2006). We use the annual mean δD record, Siple Dome A site, West Antarctica. This core is discussed in ref. 43 and at www.ncdc.noaa.gov/paleo/icecore/antarctica/siple/siple.html. We obtained the data from J. White (personal communication, 2001).

Composite Record. To form the composite record, first, each core time series was standardized by removing its mean for 1961–1990 (or 1961 until the end date) and dividing by its standard deviation for the same time period. The composite discussed here is formed by averaging these standardized records and then standardizing the average time series. Because of the lack of long-term observations over West Antarctica and the inevitable uncertainty in scaling, we present the ice core record in standardized units. For rough estimations of the temperature anomalies involved at the interesting periods discussed in the article, we use the ''composite plus scale'' approach with the ERA-40 record as calibration or with the slope of 0.60‰/K from the model result in ref. 11. We compared the results of using all cores, including those with early end dates (and different field and laboratory teams) with using only those (ITASE) cores that extend through at least 1999 and were all dated consistently and measured in the same laboratory. We do not find a significant difference between the resulting composites.

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