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An Oceanic Cold Reversal During the Last Deglaciation

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A detailed deuterium excess profile measured along the Dome C EPICA (European Project for Ice Coring in Antarctica) core reveals the timing and strength of the sea surface temperature changes at the source regions for Dome C precipitation. We infer that an Oceanic Cold Reversal took place in the southern Indian Ocean, 800 years after the Antarctic Cold Reversal. The temperature gradient between the oceanic moisture source and Antarctica is similar to the Dome C sodium profile during the deglaciation, illustrating the strong link between this gradient and the strength of the atmospheric circulation.

Triggered by changes in Earth's orbital parameters, the major climatic changes that occur during transitions between glacial and interglacial modes are sensitive to internal feedbacks such as instabilities of continental ice caps, ice albedo, greenhouse gases, and heat transport by the ocean. High-resolution cross-dated climate records from ice cores have enabled us to constrain interhemispheric phase lags over the last deglaciation and to advance our understanding of the underlying mechanisms (*1*–*3*). In the Northern Hemisphere, the large warming associated with the last deglaciation is interrupted by a return to cold conditions, the Younger Dryas, occurring between about 12.5 and 11.5 thousand years before the present (ky B.P.) (*4*). Conversely, most temperature records from Antarctica show a different interruption of their warming, the Antarctic Cold Reversal (ACR), starting around 14 ky B.P. (*5*). The antiphase between Greenland and Antarctica at the time of the Younger Dryas (a warming in inland Antarctic records at 12.5 ky B.P., when Greenland cools abruptly) is consistent with the idea of a seesaw behavior of the Atlantic thermohaline circulation (*6*), caused by a massive discharge of ice cap meltwater, which shut down thermohaline circulation, resulting in a rapid cooling in the north and a warming in the south. Some ocean sediment records in the subantarctic southern Indian Ocean show a cold reversal, similar to Antarctic records (*7*). Recent high-resolution isotopic records obtained on East Antarctic cores both from a near-coastal site at Taylor Dome (*8*) and from inland at the Dome Concordia site (*9*), confirm that the overall deglacial pattern is asynchronous between Greenland and Antarctica. Those recent results, however, suggest that the picture of a temperature seesaw may be too simplistic (the two periods of warming in Antarctica lead the abrupt transitions in Greenland, whereas the cooling after 14 ky B.P. is roughly in phase). One way to decipher this complex north-south behavior is to obtain high-resolution oceanic records on a time scale comparable with Antarctic and Greenland records.

To get such oceanic records, we used the European Project for Ice Coring in Antarctica (EPICA) core obtained at Dome Concordia (75°06′06″S 123°23′42″E, 3233 m above sea level elevation), 50 km uphill from a previous thermal core drilling carried out during the 1977–78 Antarctic field season (*10*, *11*) and 800 km from the nearest coast (Fig. 1). We have performed water stable isotopic measurements (*12*) of D/H (*9*) and $^{18}O/^{16}O$ at high analytical precision on the first 590 m of ice recovered from the EPICA core, spanning the past ~27 ky (*13*), with a temporal resolution ranging from about 20 years in the Holocene to 50 years during the last glacial (Fig. 2). Our strategy is to combine the information from these two isotopes to reconstruct on a common time scale past surface temperatures at both Dome Concordia and the oceanic moisture source. Whereas paleotemperature reconstructions from ice cores are based on the empirical relations existing between either D/H or $^{18}O/^{16}O$ and condensation temperatures, recently increasing attention has been given to the second-order parameter, the deuterium excess (*14*): $d = \delta D - 8 \times \delta^{18}O$. This parameter reflects the slightly different behavior of hydrogen and oxygen isotopes during kinetic fractionation of H_2O at evaporation (*15*) and snow formation (*16*). Observations of surface isotopic distributions and theoretical isotopic modeling studies show the large imprint of sea surface temperature (SST) and relative humidity at the moisture source and the secondary imprint of the site temperature and of the ocean isotopic composition on *d* in polar precipitation (*17*–*19*). Variations of *d* have been used to quantitatively reconstruct past ocean surface changes at time scales varying between 100,000 and 1000 years (*20*, *21*). We apply this approach to interpret the Dome C EPICA record (Fig. 2).

Starting from the bottom of the EPICA core, the *d* values decrease from 7 per mil (‰) toward a broad minimum of 5.5‰ at 18 ± 2 ky B.P. (Fig. 2). From the end of the glacial period, *d* increases in two steps toward a maximum of approximately 9.5‰ in the early Holocene (8.5 ky B.P.). This long-term trend of the deuterium excess may reflect the impact of Earth's obliquity on the delivery of moisture to the polar regions, as shown for the long Vostok record (*20*). Spectral analyses conducted on the deuterium excess profile show periodicity already noted in Holocene *d* records (*22*) at 110 and 140 years, as well as a specific centennial periodicity (700 years). Three millennial-scale oscillations in deuterium excess of 1 to 2‰ can also be seen during the glacial period (between 20 and 25 ky B.P.). During the Holocene, the deuterium excess shows four aperiodic millennial-scale 1 to 2‰ oscillations superimposed onto a generally decreasing trend from about 8 to 4.5 ky B.P. and quite stable values afterward, reaching the present-day value of 9‰. Apparently, ice cores located deep within the interior of the continent (Vostok, Dome B) and receiving moisture mainly from low latitudes show a *d* increase during the Holocene (*22*), similar to the increase in tropical SST. On the contrary, ice cores closer to the coast, such as Dome C or Law Dome (*23*), will receive moisture mainly from the southern temperate ocean, reflecting the different pattern of SST at high latitudes during the Holocene (*22*). The opposite trends at high and low latitudes may arise from opposite trends in annual mean insolation. On the long time scale, the two-step shape pattern of the *d* record during the deglaciation mimics the similar trend in δD, with *d* lagging δD by at least 1 millennium. Specifically, during two rapid decreases in δD (at the onset of the ACR and at the end of the early Holocene optimum), the two records appear anticorrelated.

In order to reconstruct surface temperature changes at the site and in the main moisture source (the Indian Ocean at about 40°S) (*24*, *25*), we developed an inversion of the EPICA Dome C snow and ice isotopic

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composition, neglecting the influence of both relative humidity and wind changes. Two parameters of the mixed cloud isotopic model (MCIM) (*26*)—the threshold for solid precipitation and the supersaturation function—are slightly tuned in order to correctly simulate the modern isotopic values along the 1995–1996 traverse from Dumont-d'Urville to Dome Concordia (*23*), considering a dominant present-day moisture source located at 40°S (SST at 10°C). The MCIM is then run with varying initial and final climatic parameters (SST, T_o; ocean isotopic composition, $\delta^{18}O_{sw}$; site surface temperature, T_s), assuming a constant relation between condensation and surface temperature ($T_c = 0.67\ T_s - 1.2$) (*16*); and a multiple linear regression is performed to calculate the sensitivity of EPICA precipitation isotopic composition to these various parameters

$$\delta D = 7.6\ \Delta T_s - 3.6\ \Delta T_o + 5.0\ \Delta\delta^{18}O_{sw} \quad (1)$$

$$\Delta d = -0.5\ \Delta T_s + 1.3\ \Delta T_o - 2.6\ \Delta\delta^{18}O_{sw} \quad (2)$$

The simulated dependency of deuterium on surface temperature, ΔT_s (7.6‰/°C), is in reasonable agreement with data from a recent Dumont d'Urville–Dome C traverse (6.9‰/°C) (*23*). Using an estimate of $\Delta\delta^{18}O_{sw}$ from an Indian Ocean record (*27*), we infer both ΔT_s and ΔT_o from the δD and *d* records of the ice (Fig. 3A). The glacial–to–early Holocene surface temperature change at Dome Concordia is 9°C, which is in good agreement with the classical interpretation based on the use of the present-day spatial gradient as independently confirmed by various methods for the Vostok site. This Antarctic surface temperature change is twice as large as the moisture source SST change of 4.5°C, this latter value being in good agreement with SST reconstructions based on planktonic foraminifera in temperate southern ocean sediment cores (*28*).

Neglect of the influence of relative humidity changes can be seen as a limitation of our reconstruction. However, atmospheric general circulation models (AGCMs) show only very weak glacial-interglacial changes in relative humidity (*29*), and the imprint of the source relative humidity on Antarctic snow deuterium excess decreases inland (*19*). In addition, Monte Carlo simulations (*30*) have been performed with the simple isotopic model, letting both SST and relative humidity be free parameters (*31*). They show the robustness of our approach with maximum inferred glacial-interglacial changes in relative humidity of less than 2.5% and error bars on ΔT_o and ΔT_s within our estimates [±0.15°C and ±0.4°C, respectively (see Fig. 3A)]. These Monte Carlo simulations also confirm the Oceanic Cold Reversal (OCR)/ACR lag. As far as winds are concerned, they only slightly influence the deuterium excess of water vapor over the ocean, because the smooth regime of evaporation (for which the kinetic fractionation factor is relatively constant, unlike for the rough regime) largely prevails at the ocean surface (*15*). This is further justified by AGCM simulations in which both smooth and rough regimes are then considered. For example, they show little overall glacial-interglacial change in the average wind speed over the subantarctic and tropical Indian Ocean, which is one of the important contributors to Dome C precipitation.

The timing of the initial moisture source increase is in phase with the timing of the Antarctic temperature increase, about 19 ky B.P., due to compensations of site and source temperature fluctuations in the deuterium ex-

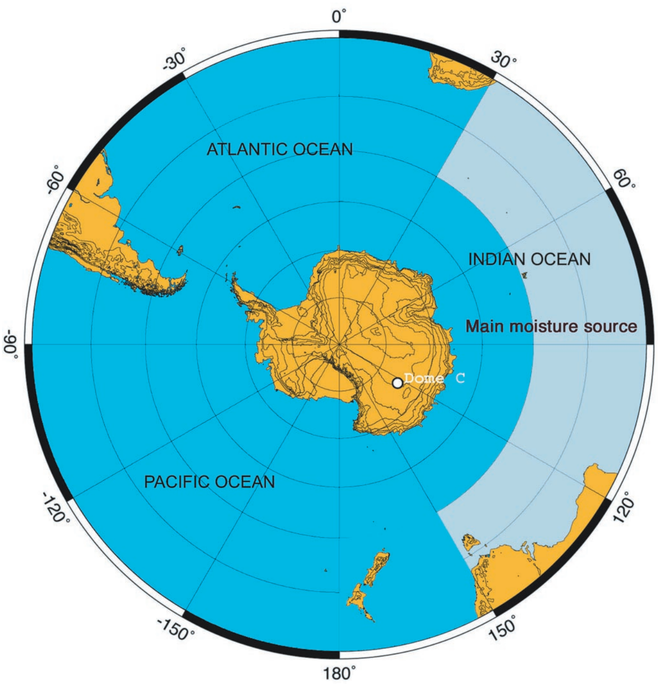

Fig. 1. Map of Antarctica showing the location of Dome C and the dominant modern moisture source (the Indian Ocean) estimated with an AGCM tagging the origin of the water (*24*).

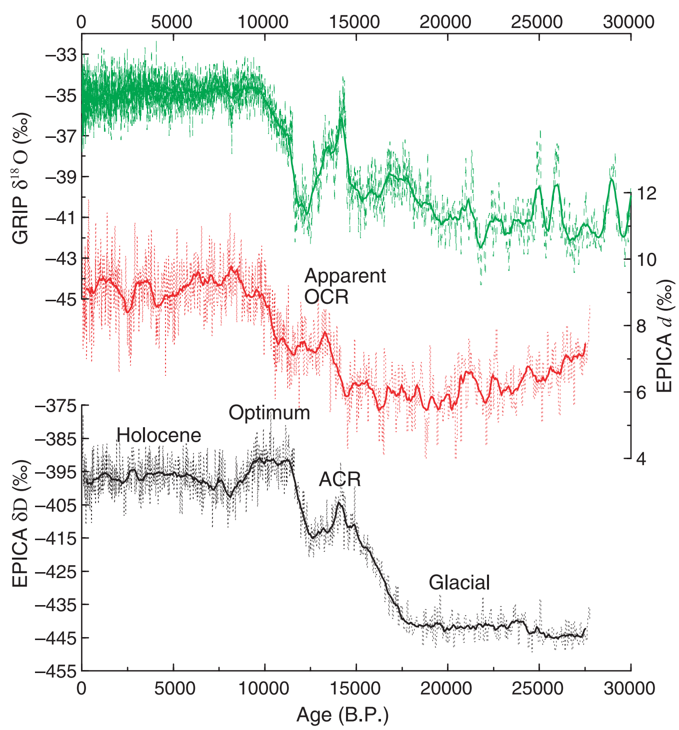

Fig. 2. EPICA deuterium (black) and deuterium excess (red) records as a function of age, raw data (dashed lines), and data smoothed with a 500-year running average (solid line). OCR is labeled "apparent" because it is defined by the deuterium excess alone. The chronology [EPICA Dome C1 (EDC1)] was established by combining an ice flow and an accumulation model with the use of dated time markers (*13*). The Greenland Ice Core Project (GRIP) $\delta^{18}O$ record (*37*) (green) has been added on a GRIP time scale in order to evaluate the results relative to the Younger Dryas in the Northern Hemisphere. The correlation (not shown here) between EPICA and GRIP using CH_4 records provides ages older than EDC1 (*13*), with a difference on the order of 400 years at about 14 ky B.P. (*9*).

cess. The moisture source exhibits a 0.8°C OCR starting around 13.2 ky B.P. (*32*), which is about 800 years after the beginning of the ACR, a 1.5°C cooling that affected the East Antarctic Plateau between ~14 and 12.5 ky B.P. (*5*, *9*). As a result, there is a large increase in the meridional temperature gradient between Dome C and its moisture source (Fig. 3C), probably associated with an intensification of the mid- to high-latitude atmospheric circulation from 14 to 11.5 ky B.P., during the Alleröd and Younger Dryas periods in the north. This increased atmospheric circulation is further supported by the parallel between our reconstructed temperature gradient and the logarithm of the sodium flux at Dome C (*2*), an index of sea salt entrainment at the sea surface and of its poleward transport (*33*). On the other hand, non–sea salt calcium (*34*), which originates from terrestrial dust, shows a less pronounced response during the ACR/OCR period, probably due to different conditions at the dust source region. The interruption of the increase in atmospheric CO_2 (*35*) occurs between the ACR and the OCR (Fig. 3B), suggesting that the southern ocean and/or the intensity of the high-latitude atmospheric circulation (dust transport) have a substantial effect on the carbon cycle. The site and source temperatures start increasing again at 12.5 ky B.P. to reach a Holocene optimum at about 9.5 ky B.P. in phase with the site temperature optimum (Fig. 3A). This optimum was initially not seen in the deuterium excess record because of the compensating impacts of both a warmer site and the higher $\delta^{18}O_{sw}$. The reconstructed source temperature seems compatible with indications of such an optimum recorded in subantarctic deep sea sediments (*22*). Similar to the patterns exhibited during the ACR onset, the source and site temperatures show opposite trends only between 9 and 8 ky B.P. This period of increased southern latitudinal temperature gradient is in phase with the last abrupt decay of the Laurentide ice cap at 8.2 ky B.P., with a widespread signature (*36*). We suggest that similar climate change mechanisms linking the two hemispheres may account for the opposite trends in Dome Concordia site and source temperatures both at the ACR onset and at 9 to 8 ky B.P. Different climate mechanisms seem to take place during warming periods, when Antarctic and subantarctic temperatures vary in phase, and cooling periods (the ACR and at the end of the optimum), when Antarctica leads the subantarctic ocean.

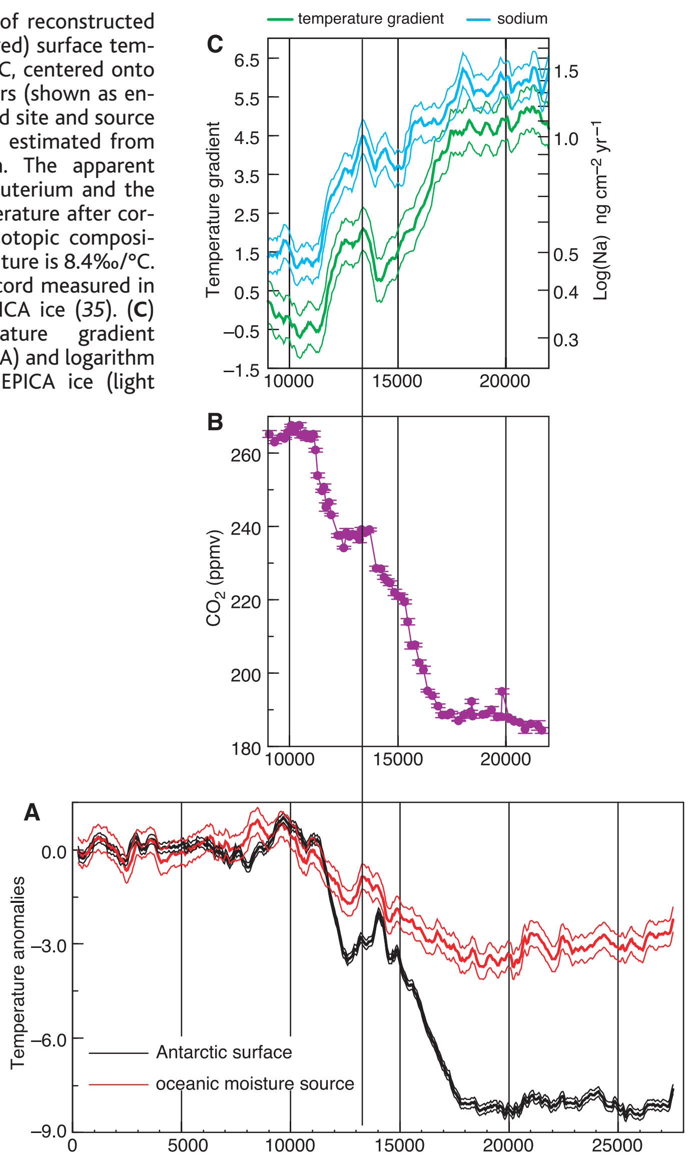

Fig. 3. (**A**) Fluctuations of reconstructed site (black) and source (red) surface temperature anomalies (in °C, centered onto modern values). Error bars (shown as envelopes) on reconstructed site and source temperatures have been estimated from the analytical precision. The apparent slope between EPICA deuterium and the reconstructed site temperature after correction for the ocean isotopic composition and surface temperature is 8.4‰/°C. (**B**) Atmospheric CO_2 record measured in the air bubbles from EPICA ice (*35*). (**C**) Source-to-site temperature gradient (green) calculated from (A) and logarithm of the sodium flux in EPICA ice (light blue) (*2*).

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12. The isotopic measurements were carried out with a depth resolution of 55 cm ("bag samples") along the whole ice core. This depth step represents a mean temporal resolution of 18, 30, and 49 years during the Holocene, deglaciation, and glacial periods, respectively. Altogether, 1050 ice samples were analyzed for both their D/H and $^{18}O/^{16}O$ isotope ratios. The δD (where $\delta D = \{[(D/H)_{sample}/(D/H)_{V\text{-}SMOW}] - 1\} \times 1000$) (V-SMOW, Vienna standard mean ocean water) measurements were carried out at Saclay using the uranium reduction technique and an automatic sample injection device online with the mass spectrometer to improve the analytical precision (±0.5‰). The $\delta^{18}O$ (where $\delta^{18}O = \{[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{V\text{-}SMOW}] - 1\} \times 1000$) measurements were carried out at Parma using the CO_2 equilibration technique by means of an automatic preparation device online with the mass spectrometer (analytical precision is ±0.05‰). In order to give a reliable interpretation of the *d* variations, it is essential to obtain the best possible accuracy with the data. For this, the $\delta^{18}O$ and δD measurements were performed on the same water samples in order to avoid small isotopic differences that can exist even between two contiguous samples, and using the same working reference waters in the two laboratories. Calibrations between our two laboratories were carried out before, during, and after the measurements, using different reference waters and samples from other ice cores. The final precision on the calculated *d* is ±0.7‰.
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30. The performed Monte Carlo simulations take into account the analytical uncertainties and the tolerance level between deuterium and deuterium excess (*21*). Several simulations were performed varying either the SST or the relative humidity (*h*) or both (assuming a realistic relation between them based on the saturation curve). In all cases where the SST was allowed to vary, the obtained SST versus site temperature profiles always showed a time lag of 800 ± 50 years between the ACR and the OCR. The simulation that varied only *h* required huge variations to explain the isotopic changes. The other simulation (varying both SST and *h*) showed very weak variations in *h* (less than 10%).
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32. The beginning of the OCR occurs about 0.9 ky before the Younger Dryas period, which can be recognized in the Dome C methane record at about 12.3 ky B.P. The uncertainty of this time lag is about 0.5 ky, taking the uncertainties of the gas-ice age difference and the time resolution of the methane record into account (*13*).
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38. This work is a contribution to EPICA, a joint European Science Foundation/European Commission (EC) scientific program, funded by the EC and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland, and the United Kingdom. This is EPICA publication no. 28. In France, EPICA is supported by the Institut Français de Recherches et Technologies Polaires. We thank F. Vimeux, M. Delmotte, U. von Grafenstein, C. Waelbroeck, and K. Rodgers for their comments; O. Cattani and S. Falourd for their careful measurements; and our many colleagues involved in drilling, science, and logistics at Dome C.

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Glacial Surface Temperatures of the Southeast Atlantic Ocean

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A detailed record of sea surface temperature from sediments of the Cape Basin in the subtropical South Atlantic indicates a previously undocumented progression of marine climate change between 41 and 18 thousand years before the present (ky B.P.), during the last glacial period. Whereas marine records typically indicate a long-term cooling into the Last Glacial Maximum (around 21 ky B.P.) consistent with gradually increasing global ice volume, the Cape Basin record documents an interval of substantial temperate ocean warming from 41 to 25 ky B.P. The pattern is similar to that expected in response to changes in insolation owing to variations in Earth's tilt.

The Southern Hemisphere oceans are thought to be an important component of the global climate system, possibly regulating glacial-to-interglacial changes in atmospheric CO_2 concentrations (*1*) and, on millennial time scales, north-south climate asynchrony (*2, 3*). We therefore sought to evaluate the temperature history of the Cape Basin, in the southeast Atlantic Ocean, which has yielded some of the most detailed ocean climate records from the Southern Hemisphere (*2, 4*). Brisk cyclonic currents scour sediment within the basin and deposit it on rapidly accumulating drifts in the southern part, at the base of the Agulhas Ridge (*5*). Sea surface temperatures (SSTs) were determined in core TN057-21-PC2 (41°08′S, 7°49′E; 4981 m water depth) from one such drift by the alkenone paleotemperature technique (*6*) using previously established protocols (*7*) and the temperature calibration of Prahl *et al.* (*8, 9*) (Fig. 1). The robustness of this technique has been demonstrated with hundreds of globally dispersed surficial sediment samples, many of which were from near our study area in the southeast Atlantic (*10*). Our results confirm the timing and approximate magnitude of SST changes during deglaciation and during oscillations of Marine Isotope Stage 3 (MIS 3) inferred previously from oxygen isotope variations in planktonic foraminifera (*2, 11*). However, we also document a previously unrecognized long-term trend in SST occurring 41 to 18 ky ago.

Holocene SSTs in TN057-21-PC2 (~19°C, Fig. 1) exceed the climatological mean annual temperature above the core site by 6°C (*12*) as a result of the winnowing and focusing of sediment from the northern part of the Cape Basin (*5*) where annual mean SSTs reach 21°C (*12*). To confirm that variations in the intensity of horizontal sediment transport did not cause the observed variations in down-core SST, we measured the activity of unsupported ^{230}Th in the sediment and used this quantity to derive sediment focusing factors (*13, 14*). Focusing factors, defined as the ratio by which the flux of horizontally transported material exceeds that of sinking material, were evaluated with respect to SST and alkenone flux (Fig. 2). No correlation exists between focusing factors and either alkenone-derived temperatures (r^2 = 0.15, Fig. 2A) or ^{230}Th-normalized alkenone fluxes (r^2 = 0.06, Fig. 2B). We thus conclude that horizontal advection of sediment did not produce the observed down-core variations in alkenone-derived SSTs. The magnitude of the focusing factors (~10 to 20) and the geographic extent of the drift deposit itself (*5*) indicate that sediments were derived from a large region, further precluding a strong influence on our record by local changes in SST or by frontal movements. Rather, alkenone unsaturation ratios in core TN057-21-PC2 provide a regional temperature signal for the Cape Basin. A precise time scale registered to the Greenland GISP2 (Greenland Ice Sheet Project 2) ice core was derived for the core (Fig. 3A) by Stoner *et al.* (*15*) by synchronizing magnetic intensity variations in the sediment to cosmogenic ^{10}Be and ^{36}Cl variations in the ice (*16*).

The total amplitude of SST in our record is 6.5°C, with minimum values of 12.5°C ~40 ky B.P. (Fig. 3A) and maximum values of ~19°C in the Holocene (Fig. 1). Temperatures were between 12.5° and 16°C in MIS 3 (>27 ky B.P.), and between 13.5° and 19°C during MIS 2 and the transition to MIS 1 (Fig. 3A). Millennial-scale temperature excursions during MIS 3 are 1° to 3°C. Deglacial warming commenced at 17.5 to 19 ky B.P. and continued until at least 11 ky B.P., with a brief plateau at ~14 to 13 ky B.P. (Fig. 3A). The glacial-Holocene temperature increase of 5.5°C (13.5° to 19°C) is comparable to recent faunal-based estimates in the temperate southeast Atlantic (*17, 18*). The pattern and timing of deglacial warming is similar to ice core paleotemperature records from Antarctica (*3*), but differs markedly from records of deglaciation in the North Atlantic where warming was interrupted by a return to cold glacial conditions during the Younger Dryas episode (~13 to 12 ky B.P.) (*19*). Observed SST changes are thus consistent with the pioneering work of Charles and co-workers (*2, 11*), who inferred local Cape Basin SST variations from high-resolution records of planktonic foraminiferal $\delta^{18}O$ values in TN057-21-PC2 and nearby core RC11-83.

An unexpected finding, however, is the warming trend at 41 to 25 ky B.P., during

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