Millennial-scale propagation of Atlantic deep waters to the glacial Southern Ocean

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[1] The compilation of changes in the magnetic properties at various sites distributed along the path of the deepwater mass in North Atlantic shows large-amplitude short-term fluctuations reflecting changes in the strength of the North Atlantic Deep Water (NADW). These changes, which suggest a two-mode deep glacial circulation dynamic, are perfectly concurrent with air temperature changes over Greenland. They also share a similar pattern with those reported in the Nd isotope ratios from the deep Cape Basin during the same time period. Greenland interstadials were accompanied by increased flow speed of NADW and relatively more NADW reaching the Southern Ocean, while during Greenland stadials and Heinrich events, both the North Atlantic flow speed of NADW and its presence in the South Atlantic were reduced. It is demonstrated that both proxies are tracing the same water mass, and their reliability for monitoring changes in the deepwater circulation is therefore clearly established. After using the climatically independent geomagnetic assisted stratigraphy to put the Northern and Southern Hemisphere records on the same age scale, the South Atlantic record appears to lag changes in North Atlantic flow speeds by approximately 860 ± 220 years during the most prominent and best defined cycles (interstadials 12 and 8). Although future work is needed, this significant offset provides a first observation and tentative quantification of the time needed for glacial northern component water to mix downward and to flow from the North to the South Atlantic.

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1. Introduction

[2] In the recent developments of paleoclimatic studies, monitoring and quantifying changes in the thermohaline circulation during the last glacial period is still a challenge. The millennial variability of the atmospheric temperature over Greenland, as recognized in the oxygen isotopic ratio of the ice and known as Dansgaard-Oeschger (D/O) cycles [*Dansgaard et al.*, 1993], can be described as an extremely rapid warming followed by a progressive cooling lasting about 1000 years. This sawtooth cycling is repetitive in time during the last glacial period. It is superimposed to a longer-periodicity sawtooth pattern starting with the warmest interstadial and finishing with the coldest stadial, also associated to the main iceberg discharges from the Laurentide ice sheets into the midlatitude North Atlantic basin [*Bond et al.*, 1993]. Models have suggested that these rapid Northern Hemisphere climatic events are linked to millennial-scale variability of the Atlantic meridional overturning circulation. However, in spite of recent advances in the reconstruction of paleocirculation changes, the mechanisms linking climate to ocean circulation are still poorly understood. This is partially due to the inability of ocean circulation records to constrain rate changes, a necessary component of general circulation models.

[3] Planktonic foraminiferal abundances and oxygen isotopic ratio at different subpolar North Atlantic sites evidenced millennial-scale N-S oscillations of the polar front and minor iceberg discharges from the northern ice caps (Fennoscandia and Greenland) [*Bond et al.*, 1993; *Cortijo et al.*, 1997; *Chapman and Shackleton*, 1998; *Elliot et al.*, 1998; *van Kreveld et al.*, 2000]. On the other hand, fewer observations are available for changes in the deepwater circulation. Some are based on benthic $\delta^{13}C$ [*Vidal et al.*, 1997; *Shackleton et al.*, 2000; *Keigwin and Boyle*, 1999] or on Cd/Ca ratio [*Keigwin and Boyle*, 1999] and they all indicate an invasion during cold periods of southern waters with a coeval decrease in the ventilation of deepwater masses. In the Southern Ocean, *Charles et al.* [1996] observed striking resemblances between the benthic foraminiferal $\delta^{13}C$ record from the deep Cape Basin and the $\delta^{18}O$ record from Greenland ice cores. Although short-lived D/O events are not all resolved in this southern record, the similarity with the Greenland ice core record is particularly clear for the most prominent and long D/O events such as D/O12 and D/O8. The authors therefore concluded about a strong influence of the Northern Hemisphere climate variability on the strength of the southward flow of the North

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Atlantic Deep Water (NADW) as recorded in the Southern Ocean nutrient proxy record.

[4] In many of these studies, the oceanic and ice records are directly correlated to one another, based on the similarity of their fluctuations assuming that they are synchronous, annulling any lead/lag relationship which may exist between them. The resolution of nutrient proxy records from both the North and South Atlantic often does not allow the documentation of millennial to submillennial-scale climatic variations. Perhaps more importantly, these proxies of ocean circulation are not independent of changes in productivity and nutrient cycling. This has led to a search for new proxies, more directly controlled by deepwater flow speed and mixing and for new long-distance correlation tools, independent from climate variability. Here we compare sedimentary records using two of these new proxies and we focus on a period of rapid glacial climate changes (MIS 3), occurring partly beyond the limit of precise radiocarbon chronological scale. One of these records reflects the changes in the strength of the overflow waters from the Nordic seas into the North Atlantic where they converge to form the NADW and the second reflects the variations in the export of NADW to the deep Cape Basin relative to the supply in southern-sourced waters. By coupling these proxies with climate-independent geomagnetic correlation tools, we give here a first attempt for assessing the real propagation time of interhemispheric ocean circulation changes.

2. North Atlantic Deep Water Strength Variations Inferred From Sedimentary Magnetic Properties

[5] Detailed analyses of sediment magnetic properties conducted on cores distributed along the path of NADW and the overflow waters from which it forms (Figure 1a) show that changes in magnetic parameters such as the anhysteretic remanent magnetization (ARM) reflect exclusively changes in concentration of magnetic minerals [*Kissel et al.*, 1999]. The studied cores are all characterized by high sedimentation rates (20 to 40 cm/ka) which, with the magnetic measurement resolution (about 4 cm), produces a time resolution of 100 to 200 years. These detailed magnetic studies constrain the nature of the mineralogy, the grain size and the concentration of the magnetic minerals in the sediments. The detailed sedimentary magnetic mineralogy analyses of the cores studied by *Kissel et al.* [1999] and *Ballini et al.* [2006] show that the coercivity force and the Curie temperature are typical for magnetites at every horizon. In addition, the hysteresis parameters measured every 2 to 5 cm indicate that all the average grain sizes are within the pseudo single-domain range, with no significant variations. The uniform nature and grain sizes of the magnetic particles therefore indicate that changes in other magnetic parameters (such as the anhysteretic remanent magnetization (ARM)) reflect exclusively changes in magnetic concentration.

[6] The main source for these magnetic particles in the subpolar North Atlantic is the northern basaltic province (related to Iceland) and we observe that their concentration decreases southward from this source to the Bermuda Rise along the NADW path. This broad north-south gradient is expected from a passive transport by overflow-generated bottom waters with no significant additional supply of magnetic minerals (Figure 1b). In addition, all deep sea cores exhibit during MIS3 short-term ARM variations which, when normalized to the average value, have a similar pattern (Figure 1c). The fluctuations in ARM could, in principle, result from differential dilution by non magnetic particles from local sources. However, the progressive decrease of magnetic content downstream along the path of the NADW and the similarity of the fluctuation pattern make this hypothesis very unlikely. Therefore, we conclude that these changes in magnetic abundance arise from a common variable, which are rapid changes in the strength of the convection in the Nordic seas, giving rise to overflow waters of different intensities remobilizing variable amounts of magnetite-rich sediments at the sill. These magnetite-rich sediments are then transported along the flow path of NADW components by near-bottom currents, as confirmed by granulometric data [*Ballini et al.*, 2006]. These magnetic parameters were also successfully used to decipher changes in the strength of the NADW during the rapid climatic events during the deglaciation and at the time of the 8.2 ka event at the Eirik drift [*Stanford et al.*, 2006; *Kleiven et al.*, 2008]. Differences in individual normalized records may be attributed to local factors. In order to filter out this local variability, we stacked the mean-normalized magnetic records. The construction of this ARM stack requires accurate correlation of all the curves on a common timescale, which is achieved by [*Kissel et al.*, 1999]: (1) correlation among cores using these short-term magnetic content cycles and (2) assignment of ages based on the Greenland ice age model [*Meese et al.*, 1997] correlating surface melting events with cold atmospheric events [*Voelker et al.*, 1998]. The a posteriori check comparing the geomagnetic field intensity records obtained from the same cores and the cosmogenic isotope record from ice indicates that the accuracy of the age assignment, i.e., the correlation with the Greenland Ice Sheet Project 2 (GISP2) ice core, is of the order of 100–150 years around 41 ka (Laschamp geomagnetic excursion) [*Laj et al.*, 2000; *Wagner et al.*, 2000].

[7] There is remarkable similarity between the drift deposit stack of magnetic proxies for overflow strength (Figure 2a) and the $\delta^{18}O$ record from GISP2 ice core [*Grootes and Stuiver*, 1997], as confirmed by the amplitudes and phasing of oscillations, including the presence of every short-lived interstadial in the magnetic record. This supports the view that reorganization of deep water formation in North Atlantic is coeval with the rapid temperature oscillations observed in the Greenland summit ice cores during MIS3. During warm interstadials, active ocean convection formed deep water in the Nordic seas, resuspending magnetite-rich sediment derived from the Nordic basaltic province at the sills and transporting it southward. During cold stadials, reduced convection, possibly driven by brine release mechanisms in the Nordic seas [*Dokken and Jansen*, 1999], yielded to reduced deep circulation, and sill sediment transport. The magnetic record supports the idea that the deep ocean circulation system in North Atlantic oscillates between

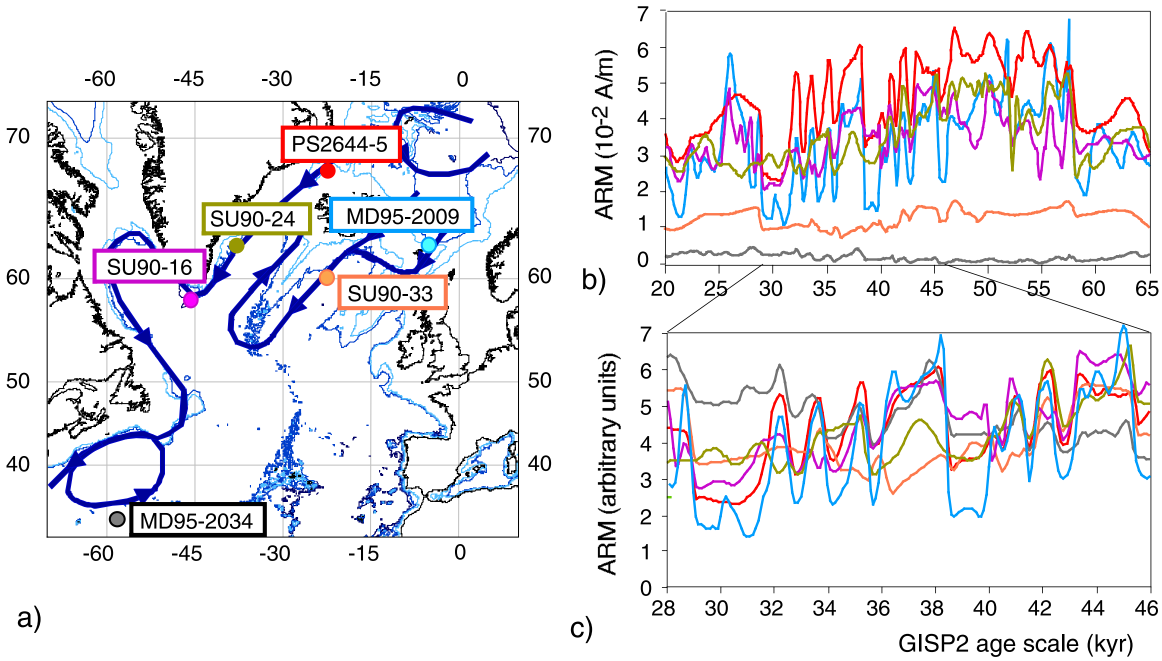

Figure 1. Magnetic property records of changes in the glacial North Atlantic Deep Water strength. (a) Schematic map showing the distribution of the cores along the North Atlantic Deep Water path (dark blue line). (b) Individual anhysteretic remanent magnetization (ARM) records reported on the same vertical scale showing a southward decrease in the average value. (c) When ARMs from the different cores are normalized to their average value, the general pattern of the rapid fluctuations is similar in all cores. All records are reported on Greenland Ice Sheet Project 2 (GISP2) age scale using the depth/age transfer proposed by *Voelker et al.* [1998] and *Kissel et al.* [1999].

two modes during interstadial-stadial cycles [*Paillard and Labeyrie*, 1994].

3. Interhemispheric Export of North Atlantic Deep Water

[8] The geographical consistency of the short-term fluctuations in our records across several climate cycles indicates that the observed pattern is not a local phenomenon in the subpolar northern latitudes but instead represents variability of the North Atlantic component of the global thermohaline circulation. To examine the interhemispheric link, our North Atlantic drift deposit stack can be compared to other records such as the ε_{Nd} of the authigenic Fe-Mn oxides component of marine sediment cores, a proxy also independent from the nutrient budget and used as a tracer for NADW flux to the Southern Ocean [*Rutberg et al.*, 2000; *Piotrowski et al.*, 2004, 2005]. A high-resolution authigenic ε_{Nd} record from the deep Cape Basin of the South Atlantic also exhibits large amplitude millennial-scale variations interpreted as variations in water mass mixing [*Piotrowski et al.*, 2004, 2005]. The ε_{Nd} variations are consistent with benthic foraminiferal $\delta^{13}C$ during MIS 3, suggesting that both proxies are primarily responding to the changing balance of NADW and AABW in the deep South Atlantic [*Charles et al.*, 1996; *Rutberg et al.*, 2000; *Ninnemann and Charles* 2002; *Piotrowski et al.*, 2004, 2005].

[9] When plotted using the original chronology, comparison of the North (magnetic mineral) and South Atlantic (Nd isotope) records indicate significantly increased northern-sourced deep water formation in the Nordic seas and export to the Southern Hemisphere were associated with the major warm Greenland interstadials (IS) 8, 12 and 14 (Figure 2b). There are two primary inferences which can be drawn from the interhemispheric similarity of the magnetic mineral and Nd isotope deepwater circulation records. The first inference is that North Atlantic convection sites changed in unison. If, for example, a significant portion of Glacial North Atlantic Intermediate Water (GNAIW) was formed south of Nordic gateways and therefore south of the basaltic zone [*Duplessy et al.*, 1988], the magnetic fluctuations would reflect only a portion of water mass formation in the North Atlantic, not necessarily in phase with the main portion. This would lead to a decoupling of the magnetic data with respect to the Nd isotope record. The striking similarity between the magnetic stack and the Nd isotope ratio record indicates that, if other convection sites existed during glacial stage, either they were concurrently active with the overflow production or only provided a minor contribution to the waters exported to the Southern Ocean. Second, the similarity between the magnetic stack and the South Atlantic ε_{Nd} record argues that the latter is reflecting changes in Atlantic circulation and not Nd isotope end-member changes caused by variations in the nature of the sediment delivery to the North Atlantic. If large-scale

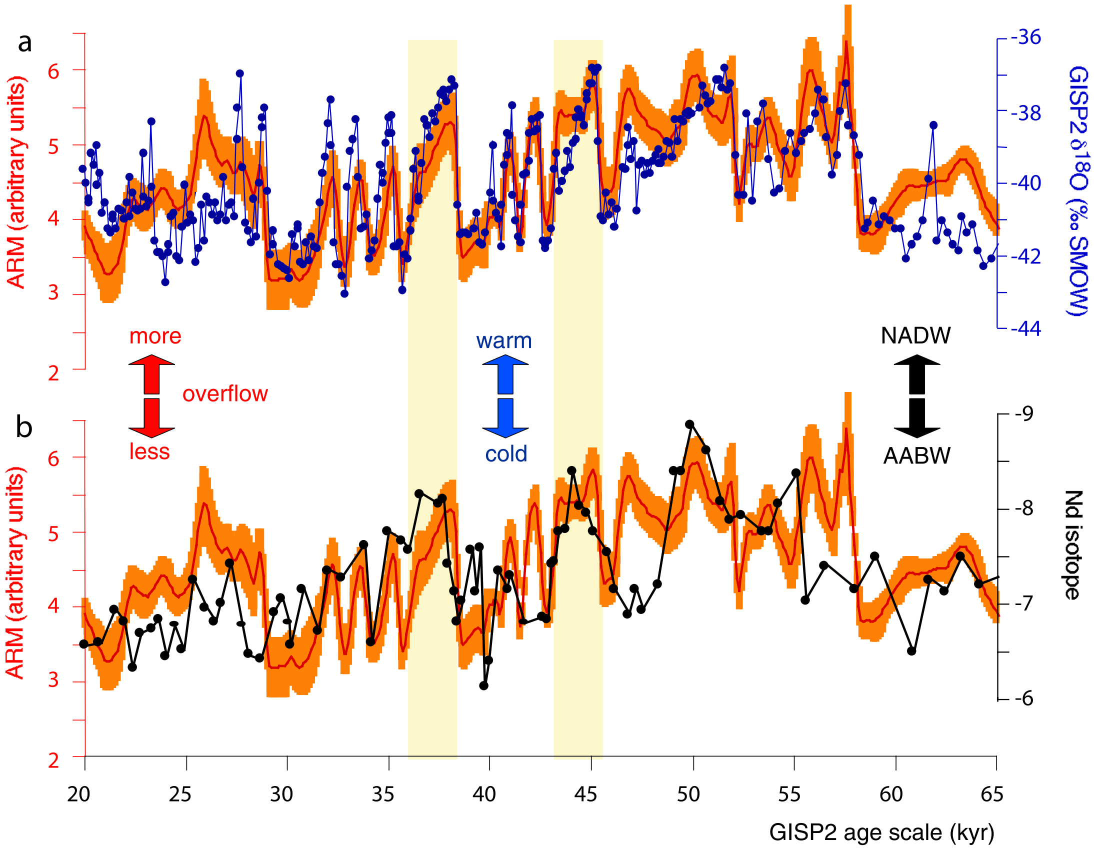

Figure 2. (a) North Atlantic drift deposit stack calculated from the six individual records shown in Figure 1 after they have been reported around the same average value. The 2σ uncertainty is calculated using bootstrap analysis. The $\delta^{18}O$ record from GISP2 ice core is also reported in blue for comparison. (b) The same North Atlantic drift deposit stack reported together with the εNd record (black) measured on Fe-Mn oxides leached from deep Cape Basin sediment core TNO57-21[*Piotrowski et al.*, 2005].

basaltic sediment-seawater exchange were predominant control on the Nd isotopic composition of North Atlantic-derived seawater, this should have become more positive during interstadials while the opposite is observed here. Although recent work on seawater samples suggests that some sediment-seawater exchange of Nd occurs along Greenland margins [*Lacan and Jeandel*, 2005], *van de Flierdt et al.* [2006] and *Foster et al.* [2007] have demonstrated that changes in the Nd isotope end-member composition of NADW were minor and not sufficient to explain the observed South Atlantic variability [*Piotrowski et al.*, 2004, 2005]. In conclusion, comparison of the two magnetic and Nd isotope records establishes the reliability of these two proxies for reconstructing past changes in Atlantic overturning. They are consistent with thermohaline circulation undergoing rapid interstadial-stadial fluctuations.

4. Temporal Relationship

[10] When strict chronological control is lacking, which is often the case in MIS 3, records of ocean circulation have usually been directly intercorrelated assuming that similar fluctuations were synchronous, thereby annulling the existence of any possible lead/lag relationship. The high fidelity and resolution of the proxy records discussed above, if they were placed on a common age scale, would allow us to determine an estimate of the time taken for a deep ocean production change in the North Atlantic to reach the deep Southern Ocean. We use the climatically independent variations in the intensity of the Earth magnetic field to correlate these widely geographically separated oceanic records. The global master curve for this time period is the global paleointensity stack for the last 75 ka (GLOPIS-75) [*Laj et al.*, 2004] resulting from the compilation of 24 high-resolution (sedimentation rates in excess of 7 cm/ka) individual paleointensity (PI) records obtained from widely distributed oceanic basins carefully correlated and placed on the GISP2 age model [*Laj et al.*, 2000, 2004]. This stack shows that the time interval during which the Earth magnetic field intensity varies the most is between 33 ka and 54 ka, where it is also punctuated by two very clear tie points constituted by the "Mono Lake" intensity low and the Laschamp excursion. We therefore focused our correlation on this time interval adjusting the paleointensity record obtained from core TNO57-21 [*Channell et al.*, 2000], reported on the same age model as the Nd isotope data, to GLOPIS-75 (Figure 3). As the individual record from the deep Cape Basin core TNO57-21 is part of GLOPIS, we

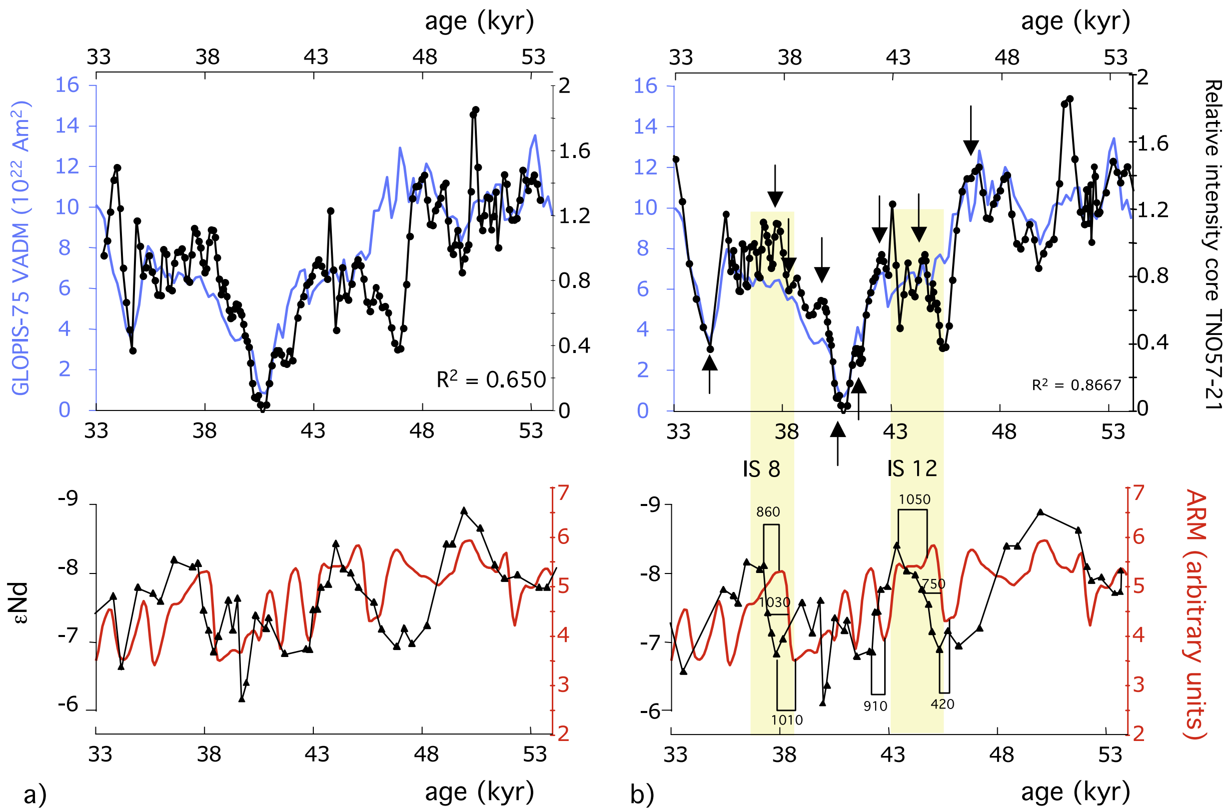

Figure 3. Effect of the time adjustment using geomagnetic-assisted stratigraphy on North Atlantic Deep Water records from the North and South Atlantic. Records reported (a) in their original chronologies and (b) after adjustment of the age scale of the southern records. (top) Modified GLOPIS-75 that is taken as a reference curve for changes in Earth magnetic field intensity is reported in blue, and the individual record from TNO57-21 is the black curve. R^2 is the correlation coefficient between the modified GLOPIS-75 and the TNO57-21 curve. The arrows on top of Figure 3b indicate the horizons used as tie points for the paleointensity correlation. (bottom) ARM stack from the North Atlantic sediments is reported in red, and the Nd isotope record is shown in black. The time shift between the two deep ocean proxies after adjustment is indicated in Figure 3b (bottom) in years.

constructed, for our purpose here, a modified GLOPIS curve in which core TNO57-21 record has not been included. This individual TNO57-21 record counted for 1 out of 24 record in the GLOPIS curve and therefore taking it out does not result in a significant difference between the published GLOPIS (24 records) and the modified GLOPIS (based on 23 records) curve. Although they are virtually identical, in particular within the time interval we focus on, we use the modified version for more rigor and to avoid circularity in age control.

[11] The PI record from core TNO57-21 was adjusted to match the modified GLOPIS-75 curve (as the master curve) and the correlation horizons used are the intensity maxima between 46 and 48 ka (GISP2 timescale) and the decreasing and increasing slopes that define the Laschamp event. The geomagnetic intensity records from the deep Cape Basin exhibit a minimum at about 46 ka in their independent chronologies. This is typical of these cores which form the bulk (4/5 cores) of the SAPIS stack originating from a very small geographic area, but it is not observed elsewhere [*Laj et al.*, 2004]. No characteristic tie point is therefore identified in the master GLOPIS-75 curve to correlate this minimum that is passively moved to 45.6 ka by the time adjustment. Doing this increases the correlation coefficient between the global stack and the Atlantic paleointensity curve in the interval 30–54 ka from a r^2 value of 0.695 to 0.839.

[12] Using the published chronology [*Charles et al.*, 1996; *Ninnemann and Charles*, 2002; *Piotrowski et al.*, 2005], the paleointensity record of TN057-21 core has a tendency to precede the modified GLOPIS-75 stack (Figure 3a), which means that, after time adjustment, South Atlantic water mass record has a tendency to lag the North Atlantic circulation record. Although the difference in the resolution of the different proxy records does not allow this comparison to be made for short-lived events, it appears that after time adjustment (Figure 3b), at each main Heinrich/interstadial transition (IS12 and IS8), the Nd isotope curve lags the North Atlantic circulation curve by about 860 ± 220 years on average. Possible differences between North and South Atlantic sediment magnetization lock-in depth may have contributed to this time shift. The lock in depth

reflects the ability of magnetic grains to reorient themselves to the ambient magnetic field shortly after deposition of the sediment. The question of large lock-in depth in marine sediments has been largely debated and evaluations ranging from 2 to about 10 cm have been suggested. However, a recent paper, which includes an exhaustive review of all records and laboratory experiments suggesting lock-in depths, *Tauxe et al.* [2006] concluded that no compelling evidence exists for significant lock-in depths in marine cores. This seems well to be the case for the North Atlantic cores where it has been shown that the magnetization lock-in depth, if any, is negligible when compared to other causes of errors in the age model [*Laj et al.*, 2000]. However, no evaluation of potential lock-in depth has yet been given for the Southern Ocean cores studied here. If future research suggests a large lock-in depth or bioturbation, then the error estimate on the apparent lead-lag relationship would need to be reevaluated. If we assume a commonly used value of 2–3 cm for the difference in lock-in depth between the North Atlantic cores and core TNO57-21 (accumulation rate of about 20 cm/ka), this would be likely to only contribute a maximum of 100–150 years to the apparent 860 ± 220 year delay of the Southern Ocean signal.

[13] Our propagation time estimate is also dependent upon the pathway of circulation between the North Atlantic overflow sites and the deep South Atlantic Cape Basin. Modern deep water does not circulate from the North Atlantic overflow sites directly to the deep South Atlantic Cape Basin, as evidenced by the strong salinity and silica gradients at 3.5 to 4.0 km near 40°S in the modern Southern Ocean [*Orsi and Whitworth*, 2007]. This necessitates dipycnal mixture of the Northern Hemisphere-derived chemical signal downward from the depth of NADW to the abyssal Cape Basin. If glacial meridional circulation occurred at shallower depths than it does today, then the effective pathway between the intermediate depth North Atlantic and deep South Atlantic Cape Basin, where our records are located, would be effectively lengthened. The *Adkins et al.* [2002] pore water salinity measurements suggested that the deep Southern Atlantic was filled with a dense southern-sourced water during the glacial period. If the vertical density stratification of the South Atlantic was increased during MIS 3 Heinrich stadials, then at the inception of each major interstadial the northern component water could not immediately transmit the circulation signal to the abyssal Cape Basin. The transmission of a North Atlantic signal to the deep South Atlantic would have been delayed until the density contrast between Glacial North Atlantic Intermediate Water and Antarctic Bottom Water was reduced by dipycnal mixing. The lag between our records therefore also reflects the time needed for northern component water to mix downward and replace the AABW, in addition to the time necessary for deep water to flow from the North to the South Atlantic. Depending upon how the vertical water mass structure and density of the Southern Ocean changed during stadial-interstadial transitions, an additional time delay may have been necessary for the Northern Hemisphere–derived Nd isotope signal to circulate and mix to the Cape Basin core site. It is also possible that the northern-derived water mass may have needed to mix throughout part of the volume of the Southern Ocean, slowly modifying its Nd isotopic composition, before this signal was recirculated to the Cape Basin. This suggests that Northern to Southern Hemisphere propagation of water masses could have occurred on shorter timescales than the North Atlantic to deep Cape Basin propagation time of the chemical signal. If additional circulation pathway complexities occurred, then the 860 ± 220 years which we calculated is a maximum estimate for interhemispheric signal propagation.

[14] Atlantic meridional overturning changes have also been suggested as a possible mechanism of generating phasing relationships between northern and Southern Hemisphere climate records [*Broecker*, 1998]. Despite possible complexities, the propagation time that we have calculated has important implications for interhemispheric and global paleoclimate. The estimation of a 860 ± 220 year lag in the South Atlantic is not inconsistent with radiocarbon data obtained for the Last Glacial Maximum (LGM) [*Adkins and Pasquero*, 2004] and with models which also report during MIS3 higher atmospheric radiocarbon content, i.e., reduced overturning, at each major cold event over Greenland [*Laj et al.*, 2002; *Hughen et al.*, 2004]. We cannot completely discount the possibility that the Greenland and Antarctica temperature variations were independently forced with a ~900 year phasing and this signal was then transferred to the deep ocean by changing northern and southern deep water formation. However, our estimate is most simply interpreted as the time necessary to establish a north to south transmission of a circulation signal along the deep flow path of the MOC during a stadial-to-interstadial transition. The lead lag relationship is additionally dependent on the exact circulation pathway and relative density contrast of Atlantic water masses. Though future work is needed to further refine the interhemispheric propagation times of deep ocean water mass transfer, this study exhibits a first observation and quantification of the MOCs role in interhemispheric temperature phasing.

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