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Enhanced Arabian Sea intermediate water flow during glacial North Atlantic cold phases

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ABSTRACT

During the last glacial period, polar ice cores indicate climate asynchrony between the poles at the millennial time-scale. Yet, surface ocean circulation in large parts of the globe varied in tune with Greenland temperature fluctuations suggesting that any anti-phase behavior to a substantial degree must lie in the deeper global ocean circulation which is poorly understood outside the Atlantic Ocean. Here we present data from the north-western Indian Ocean which indicate that the timing of maxima in northward extensions of glacial Antarctic Intermediate Water (GAAIW) coincides with dramatically reduced thermohaline overturn in the North Atlantic associated with the Heinrich-ice surge events (HE). The repeated expansion of the GAAIW during HEs, recorded far north of the equator in the Arabian Sea, suggests that southern hemisphere driven intermediate water mass variability forms an integral part of the inter-hemisphere asynchronous climate change behavior at the millennial time-scale.

1. Introduction

Glacial climate was dominated by rapid changes at the millennial time-scale, first discovered in Greenland ice core temperature records (Dansgaard et al., 1993), i.e. the so-called Dansgaard–Oeschger events (D–O-events). Glacial surface ocean conditions in the N-Atlantic (Shackleton et al., 2000), the SW-Pacific (Pahnke et al., 2003; Pahnke and Zahn, 2005) and the northern Indian Ocean (Schulz et al., 1998; Ivanochko et al., 2005 and references therein) varied synchronously with Greenland temperature fluctuations. In the past, reductions in intermediate/deepwater flow occurred repeatedly in the N-Atlantic during Heinrich Events (HEs) (Sarnthein et al., 1994; Jung, 1996). These HEs were caused by massive ice-surge events which recurrently punctuated N-Atlantic climate as part of the millennial time-scale Dansgaard–Oeschger variability.

Even though it is increasingly recognized that intermediate/deepwater variations originating in the southern hemisphere are major factors in defining the state of the global thermohaline circulation (THC), the involvement of southern hemisphere driven changes in ocean circulation at depth is poorly documented. Today, some of the world ocean's most important intermediate/deepwater masses originate around Antarctica (Emery and Meincke, 1986), where surface waters, due to density increase from lowered temperatures and sea ice formation, sink and flush the intermediate and bottom water layers of parts of the world ocean. The detailed history of the intensity of these water masses is poorly known. Sediment proxy data reflecting core intermediate water circulation <2000 m in the Indian Ocean are rare. There is one high-resolution record in the SW-Pacific that shows intensified Antarctic Intermediate Water (AAIW) during the equivalent periods of the HEs (Pahnke and Zahn, 2005). Upper deepwater circulation in the eastern Indian Ocean was also slightly enhanced during the equivalent periods of the HEs (Waelbroeck et al., 2006) below 2000 m water depth. This anti-phase behaviour of southern source AAIW and NADW at the millennial time-scale during the glacial period, however, requires more study. Here, new Arabian Sea stable isotope records derived from sediments collected off Somalia are presented with the aim to reconstruct the variability of glacial intermediate water circulation in the north-western Indian Ocean at the millennial time-scale. In a broader context, we discuss its implications for the THC.

2. Study site, methodology and background

Sediment Core NIOP 905 was retrieved from the continental slope off Somalia during the Netherlands Indian Ocean expedition in 1993 from a water depth of 1580 m. The records of the stable oxygen isotope composition of the planktic foraminifera *Neogloboquadrina*

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dutertrei and the nitrogen isotope values of the bulk sediment were generated at a 2.5 cm sample spacing (Ivanochko et al., 2005). Here, we establish the benthic stable isotope record. The upper 300 cm, equivalent to the last 11 ka, of this record is taken from (Jung et al., 2001). For the older sections, the oxygen and carbon isotope records are based on averages of multiple single specimen analysis of the epibenthic foraminifera *C. kullenbergi*. In a few limited cases *Cibicidoides* spp. were used to avoid gaps in the record where *C. kullenbergi* was rare. The data are made available via the World Data Center for Paleoclimatology in Boulder (www.ncdc.noaa.gov/paleo/paleo.html).

The age model for Core NIOP 905 is taken from (Ivanochko et al., 2005) and is based solely on 24 AMS^{14}C-dates for the top part of the sediment sequence. In addition, the close pattern similarity within this interval of surface ocean chemistry changes, i.e. planktonic foraminiferal $\delta^{18}O$ and the nitrogen isotope changes, with the Greenland

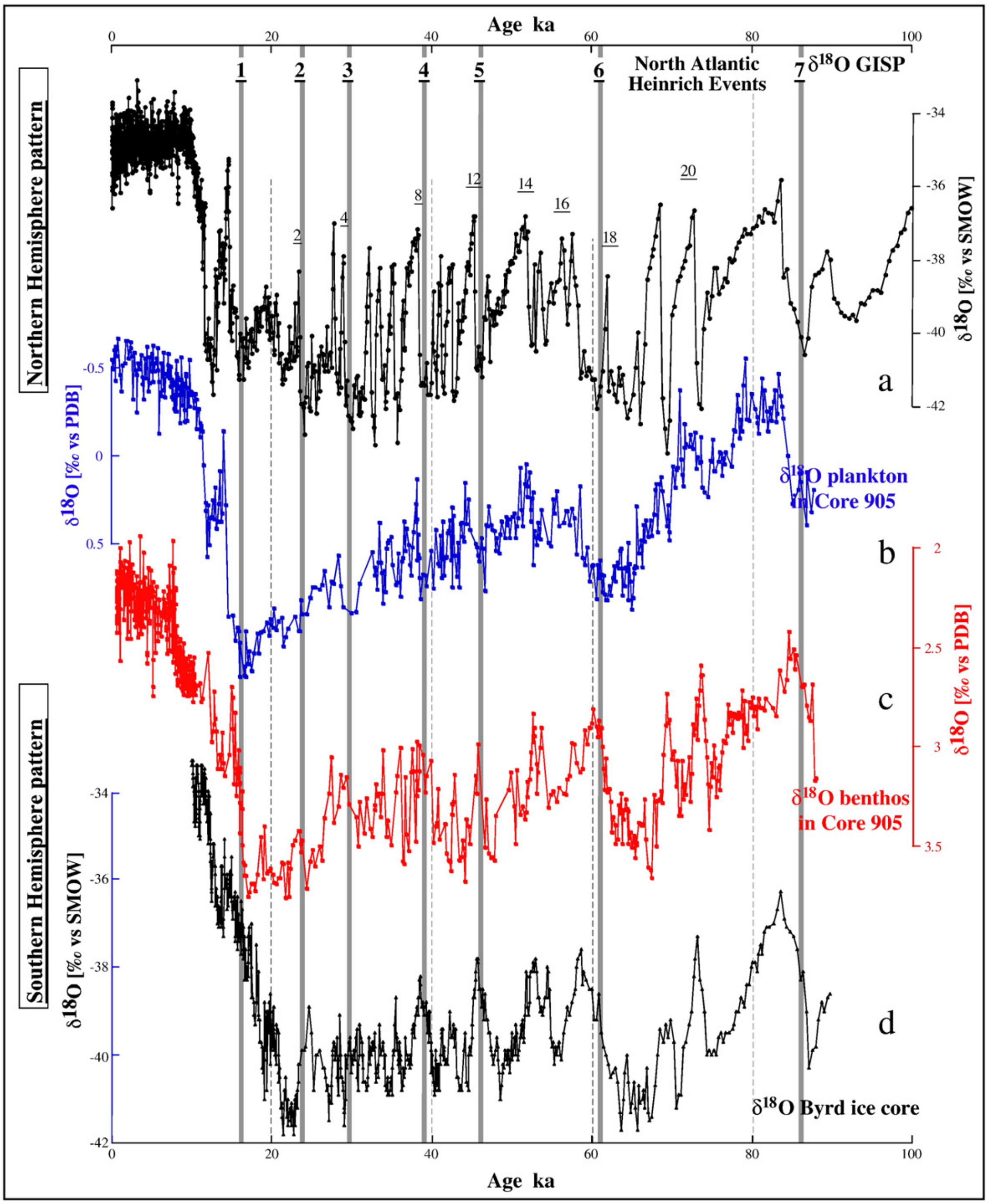

Fig. 1. Interhemispheric climate change: Comparison of (top to bottom) the stable oxygen isotope record of the Greenland GISP ice core (a, (Blunier and Brook, 2001) and references therein), the stable oxygen isotope records of the planktic foraminifera *N. dutertrei* (b) and the epibenthic foraminifera *C. kullenbergi* (1c; see main text also) and the Antarctic Byrd ice core (d). The age model of Core NIOP 905 is from (Ivanochko et al., 2005). Vertical grey bars indicate location of the North Atlantic HEs. For the present comparison we used the ice core chronologies established by (Blunier and Brook, 2001). We are aware of the ongoing discussion on revisions in ice core chronologies e.g. (Shackleton et al., 2004) (and references therein). Potential age adjustments, however, would not affect the main conclusions of the present work. The CH_4-phase locked time series (Blunier and Brook, 2001; EPICA, 2006) and references therein) established a common time frame for the Greenland and Antarctic ice core records. Adjusted ages for specific sections of either record would affect the absolute, but not the relative timing of specific climate events. More importantly, the sediment data generated for the present study are based on the same set of samples. Hence, the phasing of events, when comparing sea surface and deep ocean variations in the Arabian Sea, is largely independent of the absolute chronology.

δ^{18}O-record (see Fig. 1), suggests a climatic teleconnection between the two regions. Assuming, that this unique climatic relationship was also present beyond the time interval covered by the radiocarbon dating method, the timing of variations in the surface ocean chemistry records was tuned to match Greenland ice core δ^{18}O-changes (for details see (Ivanochko et al., 2005));(Schulz et al., 1998; Altabet Mark et al., 2002). Using this method, the base of Core NIOP 905 at 1500 cm reaches roughly 90 ka. Hence, the Core NIOP 905 record covers the time period with the most pronounced Dansgaard–Oeschger type cyclicity at a 100–300 yr resolution. In order to visualize the results at the millennial time-scale and to reduce sub-millennial-scale noise, further data processing was performed. We applied a straightforward approach using a simple-time constraint-running mean filter with a time window of 700 yrs. Applying this filter improved the signal to noise ratio as it allowed the longer millennial time-scale events to pass and, at the high-frequency end, it sufficiently suppressed short-term noise in the record. If we had taken a slightly longer or shorter filter the main results of this study would not have been altered.

In addition we compared our new results with high-resolution records from the N-Atlantic Ocean (MD95-2042 and GIK 23414) in order to assess the broader implications of our new findings. Similar to the age-assignment strategy used for Core NIOP 905, the age models of these cores are based on AMS^{14}C-dating in the top of the records and tuning of the respective sea surface record to the Greenland ice core δ^{18}O-records in the intervals of the records beyond the reach of the radiocarbon method (Sarnthein et al., 1994; Jung, 1996; Shackleton et al., 2000; Sarnthein et al., 2001) (see Fig. 2).

Intermediate water Site NIOP 905 is currently bathed by Circum Polar Deepwater, originating from the Southern Ocean (Emery and Meincke, 1986), while at shallower depth, water masses formed in the Persian Gulf and the Red Sea prevail. At present, intermediate water masses formed in the southern hemisphere (such as AAIW) do not occur in the northern Arabian Sea (Mccarthy and Talley, 1999). During glacial periods, however, when the low glacial sea level led to a dry Persian Gulf and a strongly reduced water exchange between Red- and Arabian Sea (ref. (Siddall et al., 2003) and references therein), a potentially intensified AAIW circulation may have reached the Arabian Sea. AAIW-formation in the modern ocean primarily occurs in the southeastern Pacific and the southwestern Atlantic Ocean (Sloyan and Rintoul, 2001) where it involves mixing of cold and fresh Antarctic surface waters with warm and salty subtropical gyre waters. In the southwest Indian Ocean, AAIW has been recently documented to be an integral part of the circulation in the Mozambique Channel with temperatures of 4–7 °C (De Ruijter et al., 2002), i.e. on average 1.5–2 °C warmer than the bottom water temperature at site NIOP 905 (Jung et al., 2001).

3. Results and discussion

3.1. Phasing of surface and intermediate water variability in the Arabian Sea

Oxygen isotope ratios from planktic foraminifera and nitrogen isotopes from sediment organic matter from Core NIOP 905 provide information on monsoon controlled surface ocean changes in the Arabian Sea. The timing of the variability in these surface ocean proxy records appears in phase with Greenland temperature variations at the millennial time-scale (Ivanochko et al., 2005). The timing of intermediate water changes in Core NIOP 905, recorded by the oxygen isotope ratio in tests of epibenthic foraminifera, however, strikingly differs from the timing of surface ocean changes (Fig. 1a, b, c; Supplementary Fig. 1). Changes at intermediate water depth are consistently out of phase with the changes in surface water (Fig. 1c; Supplementary Fig. 1). Whilst the oxygen isotope change at the sea surface occurred roughly in phase with the Greenland δ^{18}O-change, intermediate water oxygen isotope changes show similarities in phasing with millennial time-scale Antarctic climate variations (Fig. 1c, d).

3.2. Potential impact of locally formed intermediate water masses

Theoretically, the benthic isotope time-series of Core NIOP 905 may represent variations in locally formed water masses such as Red Sea Water (RSW) or Persian Gulf Water (PGW). In the modern Arabian Sea, RSW and PGW settle at water depths of ~800 m and ~300 m, respectively (Shapiro and Meschanov, 1991; Prasanna Kumar and Prasad, 1999). Hence, today deepwater at Site NIOP 905 (depth 1580 m) is not affected by these water masses.

During the glacial period, RSW and PGW may have settled deeper in the water column. The question arises whether sea level lowering had impeded RSW and PGW outflow during the glacial period. Today, the average water depth of the Persian Gulf is ~50 m. With a glacial sea level being at least 50–60 m lower, which has been the case for most of the glacial period, the Persian Gulf was largely dry and thus PGW could not have contributed significantly to the local Arabian Sea intermediate water masses. The exchange between the Arabian Sea and the Red Sea is controlled by the Strait of Bab el Mandeb that currently has a sill depth of ~137 m. During MIS 2, sea level had dropped by ~120 m reducing the sill depth to a few tens of meters, which must have prevented practically any RSW outflow. We conclude that the observed benthic oxygen and carbon isotope changes in Core NIOP 905 during MIS 2 cannot be explained by the influence of RSW or PGW. It is much more likely that the roughly simultaneous changes in benthic carbon and oxygen isotopes in Core NIOP 905 (for more detail, see further below; Figs. 1 and 4) would reflect episodic advection of a remote water mass such as glacial AAIW (GAAIW) in the area. A minor influence of RSW during MIS3, and in particular during MIS5, cannot be ruled out at this stage. The regular pattern in the oxygen and carbon isotope changes in Core NIOP 905 across glacial time periods encompassing MIS5-2, however, suggests that the processes having caused the observed isotope changes were largely indifferent to the overall state of the glaciation (i.e. sea level change), suggesting that a local overprint was largely insignificant.

3.3. An Antarctic view and global implications

The close similarity in timing between Antarctic climate change (Blunier et al., 1998; EPICA, 2006) and the deepwater oxygen isotope variability in Core NIOP 905 (Fig. 1) points to a close relationship of Antarctic climate change and glacial intermediate water variation off Somalia. Hence, in the likely absence of significant contributions of locally formed glacial intermediate water masses (see Section 3.2), the repeated reduction in oxygen isotope values in Core NIOP 905 must reflect associated warming periods, or periods of relative warming of intermediate water versus deepwater in the source regions of GAAIW in the southern hemisphere (Blunier et al., 1998; EPICA, 2006). Part of the oxygen isotope change, however, is due to changes in ice volume sensu (Shackleton et al., 2000). We propose a scenario, where possibly half of the oxygen isotope change reflects variations in global ice volume and the remaining portion of the change reflects a temperature rise of up to 2 °C, largely in line with a previous approach in the Pacific Ocean (Stott et al., 2007).

The view that glacial intermediate water changes recorded off Somalia probably reflect those of southern hemisphere GAAIW is fully in line with previous studies suggesting that the overall contribution of southern hemisphere intermediate (Kallel et al., 1988; Boyle et al., 1995; Pahnke and Zahn, 2005) and deepwater (Sarnthein et al., 1994; Keeling and Stephens Britton, 2001; Adkins et al., 2002) was higher during glacial time periods. Our results emphasize the importance of enhanced intermediate water circulation by showing that not only the SW-Pacific but also parts of the Indian Ocean up to the Arabian Sea were affected by repeatedly strengthened GAAIW formation.

To further investigate the intermediate water history of the Arabian Sea, we use carbon isotopes of epibenthic foraminifera which reflect the δ^{13}C-ratio of dissolved inorganic carbon (DIC) of

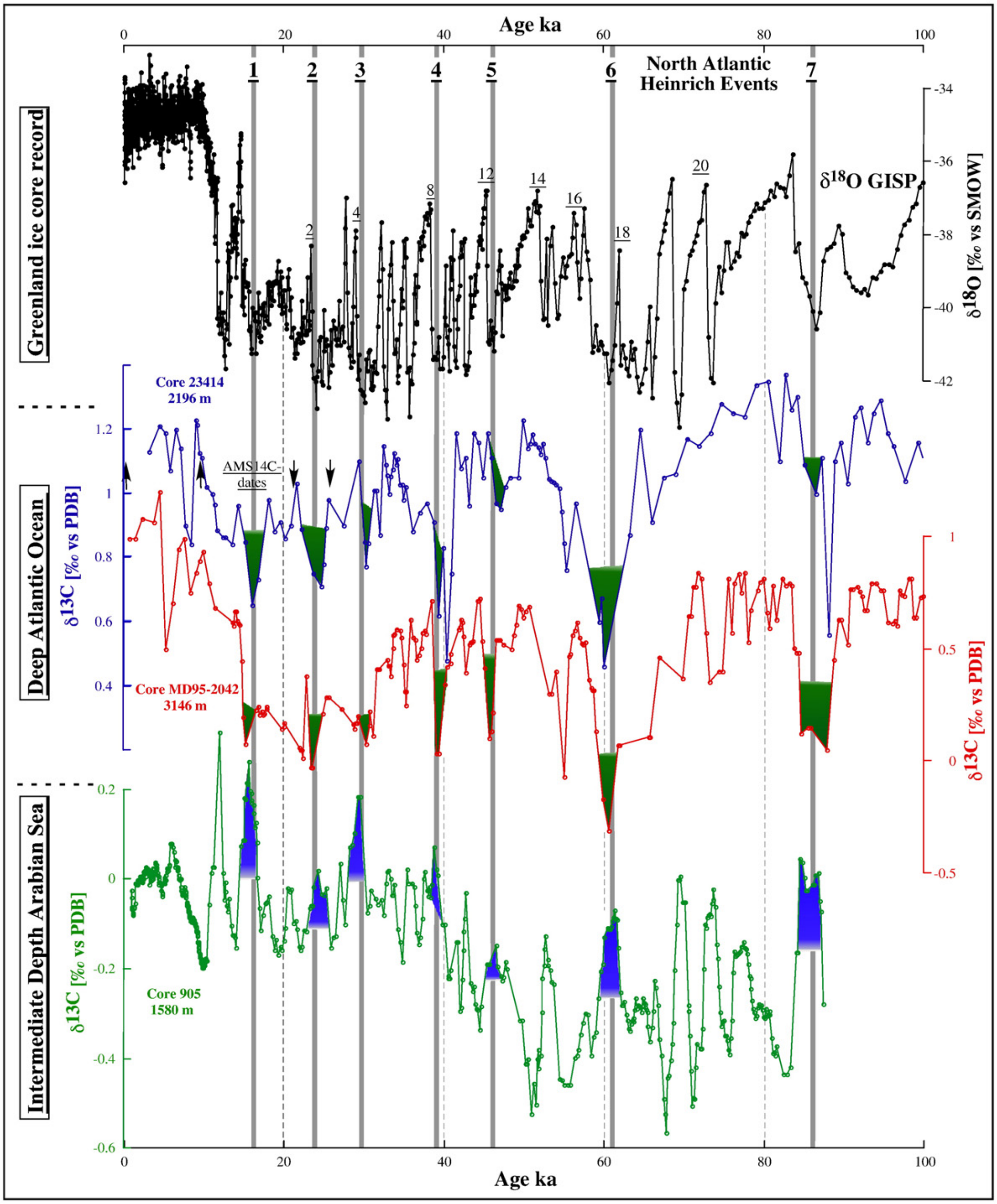

Fig. 2. Indo-Atlantic intermediate to deep-ocean circulation histories: Comparison of the benthic NIOP 905 carbon isotope data with those of Core MD95-2042 that was recovered from a water depth of 3146 m on the Iberian Margin (Shackleton et al., 2000) and Core GIK 23414 (recovered from 2196 m water depth at Rockall Plateau (Sarnthein et al., 1994; Jung, 1996)). Similar to the age-assignment strategy used for Core NIOP 905, the age model of Core MD95-2042 is based on a combination of AMS^{14}C-dating and tuning of the respective sea surface record to Greenland ice core records (Shackleton et al., 2000). Hence, the age models used for both records were independently established, albeit constrained by Greenland ice core chronology. In order to improve graphical comparability and to correct for mutual slight differences in temporal resolution a 700-yr running mean filter was applied (Core NIOP 905). The age model of Core GIK 23414 is slightly modified from (Sarnthein et al., 1994; Jung, 1996).

ambient seawater. The δ^{13}C-ratio serves as a proxy for ageing of the water mass along its flow path, i.e. the ventilation state of the ocean. High δ^{13}C-values in newly formed water decrease by the continuous addition of isotopically light organic carbon originating from remineralization of organic matter from the surface layers. En-route, this process results in δ^{13}C-reduction of the DIC pool. It could also, however, partly reflect potential changes in surface ocean conditions in the water mass source regions. Unfortunately the δ^{13}C-values in the DIC of the GAAIW source water are unknown through time. These preformed values are influenced by processes such as variations in productivity, or variations in sea ice extent which modulate the air–sea exchange and temperature acting on carbon isotope fractionation during the air–sea equilibration of CO_2.

Although δ^{13}C-values of DIC in the source areas of GAAIW have been modulated by these processes, the δ^{13}C-signature remains useful to identify water masses in the world ocean. AAIW in the Indian and Pacific Ocean for example, has a high δ^{13}C-value of DIC in the modern ocean (Kroopnick, 1985; Charles and Fairbanks, 1992) and the δ^{13}C-value was probably also high in the past. We assume that, although preformed carbon isotope values of GAAIW in the source area have changed through time, its generally high δ^{13}C-signature relative to values of surrounding water bodies was most likely maintained. In the light of these considerations, we interpret the δ^{13}C-maxima in Core NIOP 905 to indicate episodic extensions of GAAIW into the Arabian Sea in the absence of any local water masses from the surrounding seas (Fig. 2). Similarly, δ^{13}C-maxima of intermediate water depth in the Pacific were interpreted to reflect short-term GAAIW enhancements in the southwestern Pacific (Pahnke and Zahn, 2005). The close similarity between the records confirms the prevailing influence of GAAIW in the Arabian Sea. Average SW-Pacific benthic δ^{13}C-values during the maximum peaks are roughly 0.7‰ higher than the values in Core NIOP 905 (Fig. 3) whereby the higher δ^{13}C-values off New Zealand (Pahnke and Zahn, 2005) than in the Arabian Sea suggest a closer proximity of the GAAIW source.

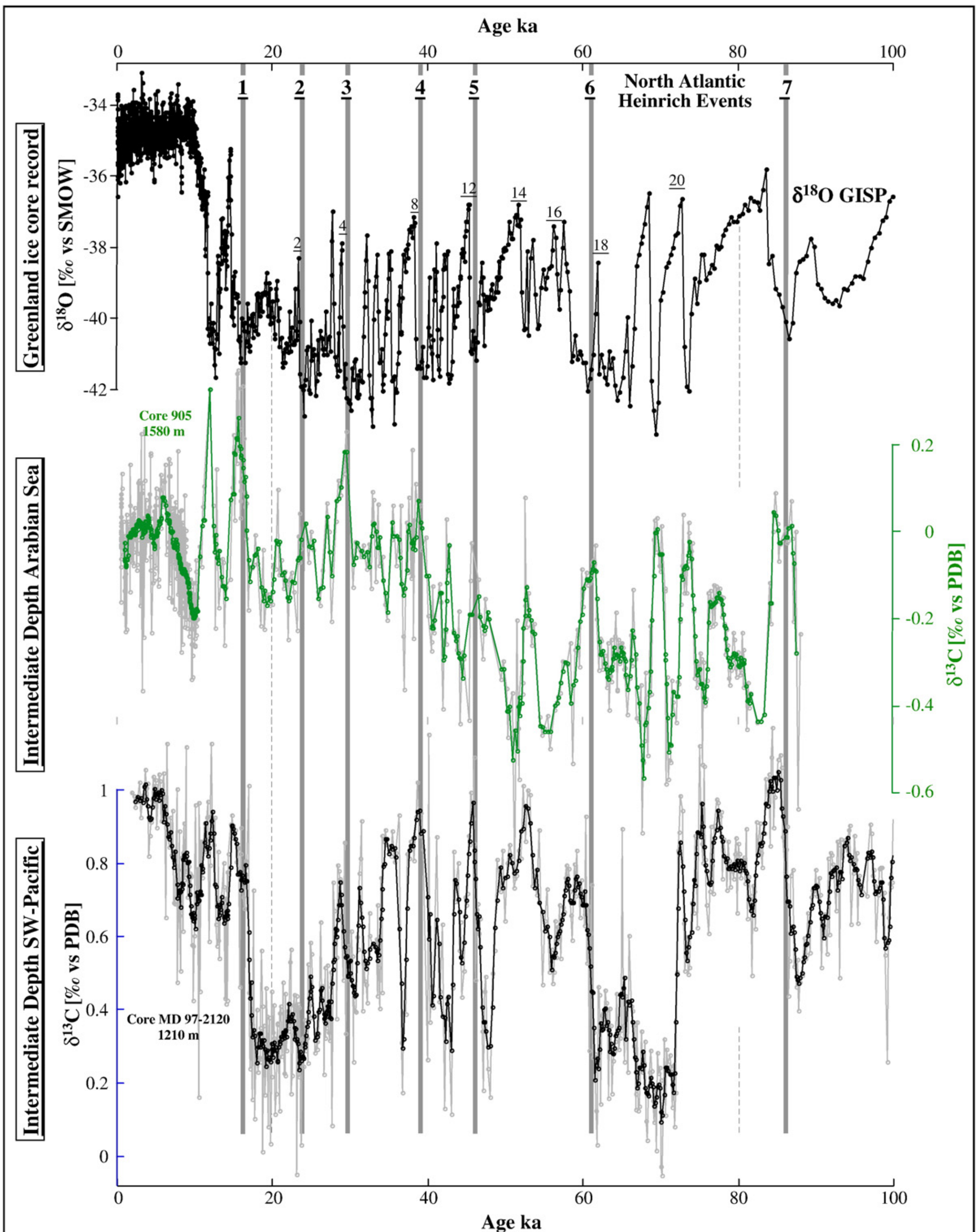

Fig. 3. Time series of benthic stable carbon isotope records of Arabian Sea Core NIOP 905 and southwest Pacific Core MD 97-2120 (Pahnke and Zahn, 2005). In order to improve graphical comparability and to correct for mutual slight differences in temporal resolution a 700-yr running mean filter was applied for both cores. Original isotope data are greyed.

In high-productivity areas, variations in the flux of organic carbon and the subsequent change in oxidation at the sea floor may locally overprint the water mass δ^{13}C-signal (Mackensen effect). In the Arabian Sea bio-production varied at the millennial time-scale (Ivanochko et al., 2005). Hence, these variations could have affected the benthic δ^{13}C-record of Core NIOP 905. Such a scenario requires a simultaneous anti-phase change in both, δ^{15}N (surface ocean proxy closely related to productivity) and benthic carbon isotopes (intermediate water). Visual inspection shows, however, that changes at mid-depth in Supplementary Fig. 2 occur prior to the changes at the sea surface. Also, there is no clear antiphase relationship between the δ^{15}N and the benthic carbon isotope record, in particular during MIS 3–4, arguing against a significant bioproductivity overprint of the benthic δ^{13}C-record. Although productivity changes may have had a minor effect on the δ^{13}C-values at depth, they could not have affected the respective benthic oxygen isotope record. Consequently, the close similarity of variations of benthic carbon *and* oxygen isotope records (see Fig. 4) supports the notion that changes in ocean circulation were more important for changes in the benthic δ^{13}C-record of Core NIOP 905 (see chapter 3.2). Accordingly, we conclude that the glacial benthic δ^{13}C-signal in Core NIOP 905 predominantly reflects variations in GAAIW.

3.4. Vertical extension of Heinrich-time carbon isotope maxima

To constrain the vertical extension of the intensified intermediate water circulation we compared the carbon isotope record of Core NIOP 905 with carbon isotope records from upper deepwater Cores NIOP 929 (Arabian Sea) and MD 98-2165 (eastern Indian Ocean (Waelbroeck et al., 2006); see Supplementary Fig. 3) retrieved from ~2500 m and 2100 m, respectively, significantly below Core NIOP 905 (retrieved at 1586 m). The carbon isotope records of Cores NIOP 929 and MD98-2165 (Fig. 5, Supplementary Fig. 3) show an initial rise in carbon isotope values during H1. This rise, however, is much smaller than in the carbon isotope record of Core NIOP 905 and in intermediate depth waters off New Zealand (Pahnke and Zahn, 2005) suggesting that the increased water flow was indeed largely confined to the intermediate water realm of GAAIW, as recorded in Core NIOP 905. The δ^{13}C-data of deeper Cores NIOP 929 and MD 98-2165 would reflect partial downward mixing of Core GAAIW into the deeper waters.

Wind forcing and sea ice extent appear the most important factors controlling rate of formation and properties of southern source water waters such as GAAIW (Nof, 2003; Keeling and Stephens Britton, 2001). The findings from Core NIOP 905 and from the SW-Pacific (Pahnke and Zahn, 2005), reflecting change at roughly 1500 to 1200 m water depth, respectively, imply that GAAIW settled roughly at the modern water depth, possibly slightly deeper, in line with computer simulations for the glacial world (Schmittner et al., 2007). This minor change compared to the modern situation suggests that the overall density/buoyancy change involved in modern and GAAIW formation (during N-Atlantic cold events) was comparable, arguing against a significant sea ice extent or meltwater induced slow down in GAAIW formation. This finding reiterates an earlier conclusion that a substantial part of the observed Heinrich-

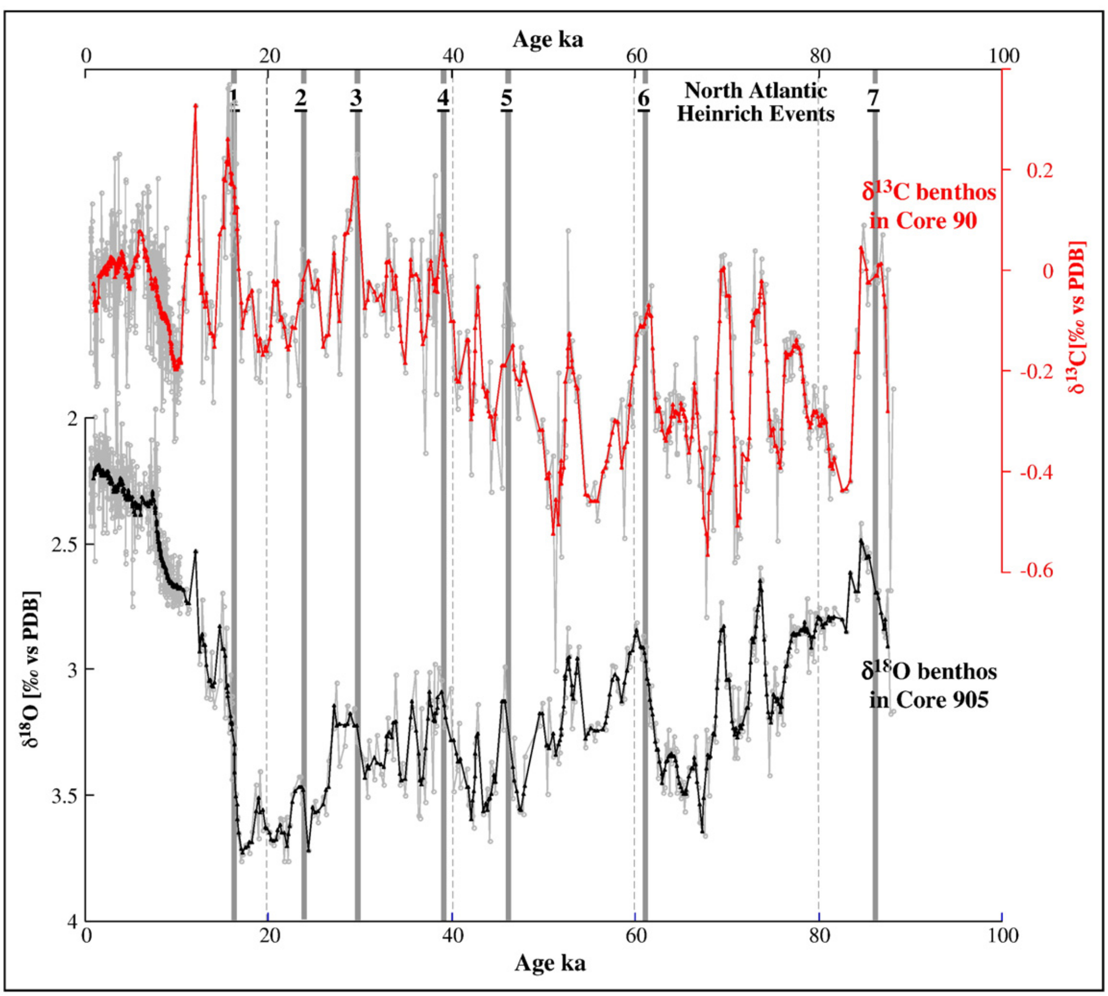

Fig. 4. Intermediate water isotope records in the Arabian Sea: Benthic stable oxygen and carbon isotope time series of Core NIOP 905. Vertical grey bars indicate location of the North Atlantic HEs. In order to improve graphical comparability a 700-yr running mean filter was applied. Original carbon and oxygen isotope data are greyed.

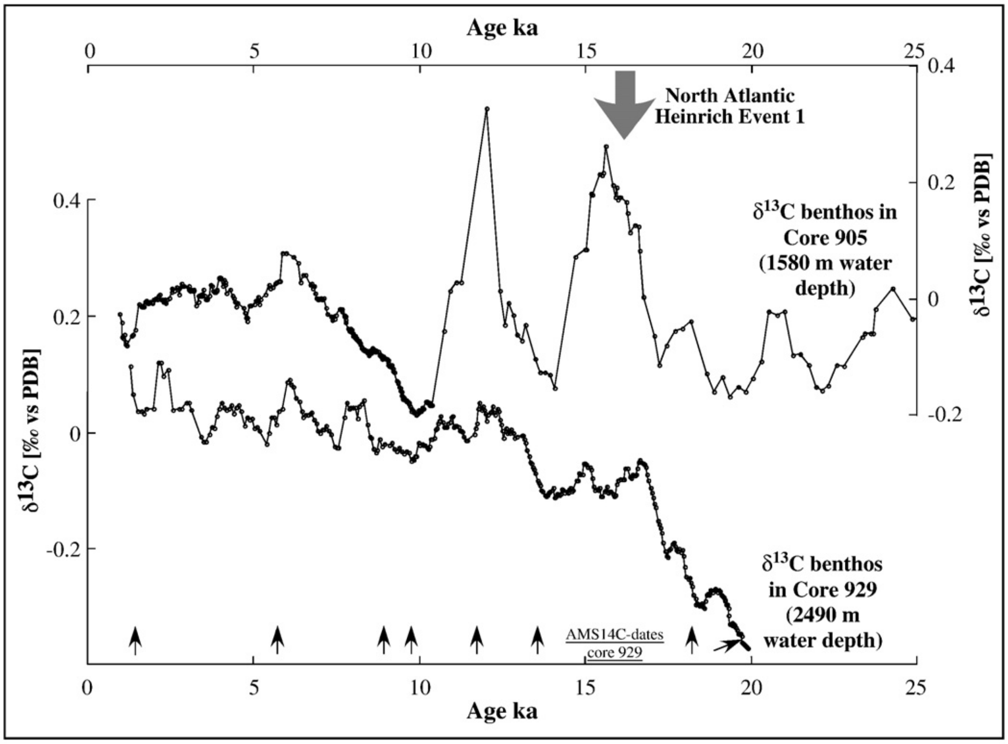

Fig. 5. Carbon isotope depth transect in the Arabian Sea: Time series of benthic stable carbon isotope records of Arabian Sea Cores NIOP 905 and NIOP 929. Core NIOP 929 is located at 13°42, 21N; 53°14,76E and was recovered from 2490 m water depth. The age model is taken from (Saher et al., 2007) (AMS dates are indicated by arrows). The carbon isotope record of Core NIOP 929 is based on the epibenthic foraminifera *C. wuellerstorfi* (analytical procedures are identical to those used for Core NIOP 905). In order to improve graphical comparability and to correct for mutual slight differences in temporal resolution a 700-yr running mean filter was applied for both cores.

time δ^{18}O-decrease probably reflects repeated temperature increases at the source of GAAIW.

3.5. An inter-ocean basin perspective

The carbon isotope results from Core NIOP 905 place the GAAIW pulses previously described for the SW-Pacific Ocean (Pahnke and Zahn, 2005) on an Indian Ocean (Indo)-southwestern Pacific scale (see Figs. 2 and 3). In order to assess the importance of GAAIW influence for the THC, we compare the deep/intermediate water histories of the Indo-southwestern Pacific and the N-Atlantic by using δ^{13}C-records of Cores NIOP 905 (Arabian Sea), MD 95-2042 (Shackleton et al., 2000) and GIK23414 (Sarnthein et al., 1994) (both N-Atlantic; Fig. 2). The results show that strength variations in the intermediate water flow in the Indo-southwestern Pacific Ocean and the N-Atlantic are in anti-phase (Fig. 2). During the HEs the well-known drawdown of deep convection in the N-Atlantic (Jung, 1996; Vidal et al., 1997) corresponds to enhanced intermediate water circulation in the Arabian Sea and also in the Indo-southwestern Pacific (Pahnke and Zahn, 2005).

Focus on the AMS^{14}C-dated – i.e. untuned – succession of events around HE1 allows for a detailed analysis of the phasing of intermediate water changes in the Arabian Sea and variations in Atlantic overturning circulation. Recent studies from the deep N-Atlantic Ocean document an early reduction in meridional overturning circulation (MOC) preceding HE1 (ref. (Hall et al., 2006) and references therein; compare Fig. 6). The onset of the enhanced GAAIW flow recorded in the Arabian Sea, although close to the detection limit of the radiocarbon method, also preceded the main N-Atlantic HE1 ice surge event (Fig. 6). Hence, within the limits of the best estimated age control, both, early N-Atlantic MOC draw down and early GAAIW intensification approaching HE1 occurred roughly synchronously within the current age model, in line with recently published data (Pahnke et al., 2008). The synchronicity of the early draw down in MOC in the N-Atlantic Ocean (Fig. 6) and peaks in GAAIW formation suggests that the THC in both hemisphere is connected, potentially as an integral part of the asynchronous climate change behaviour at the millennial time-scale, occurring between the poles.

Given the distant southern ocean origin of GAAIW recorded in Core NIOP 905, the "true" circulation event eventually recorded off Somalia related to HE1 probably occurred earlier in order to allow transit of the respective GAAIW to the Arabian Sea. Modelling experiments for the modern ocean suggest that oceanic tracer transport in deep and intermediate water masses may take a few hundred to even thousands of years to reach equilibrium (Waugh et al., 2003; Peacock and Maltrud, 2006). Accordingly, the episodically more vigorous intermediate water depth circulation, implied by the δ^{13}C-spikes in the Indo-southwest Pacific (this study, (Pahnke and Zahn, 2005)), suggests that the transit time of δ^{13}C-spiked GAAIW to the Arabian Sea probably was in the order of a few hundred years, i.e. at the lower end of the estimates for the modern ocean. This may have accounted for the minor offset in the onset of MOC-drawdown in the N-Atlantic and δ^{13}C-increase in GAAIW (Fig. 6) reiterating that the HE1 related early intensification of GAAIW and early reduction in N-Atlantic MOC occurred roughly in phase. Given the overall similarity of the phasing of the carbon isotope spikes in Core NIOP 905 with respect to those in the N-Atlantic during the HEs, we speculate that the outlined relationship between GAAIW and MOC change also holds for H2–H6 (Fig. 2).

3.6. Implications for the global thermohaline circulation

The new results of Core NIOP 905 emphasise the relevance of variations in southern ocean circulation for global climate and the implications for the THC. Within the conceptual model of the global THC, continuity of water flow/exchange between ocean basins is crucial for maintaining stability of the circulation system. Modelling

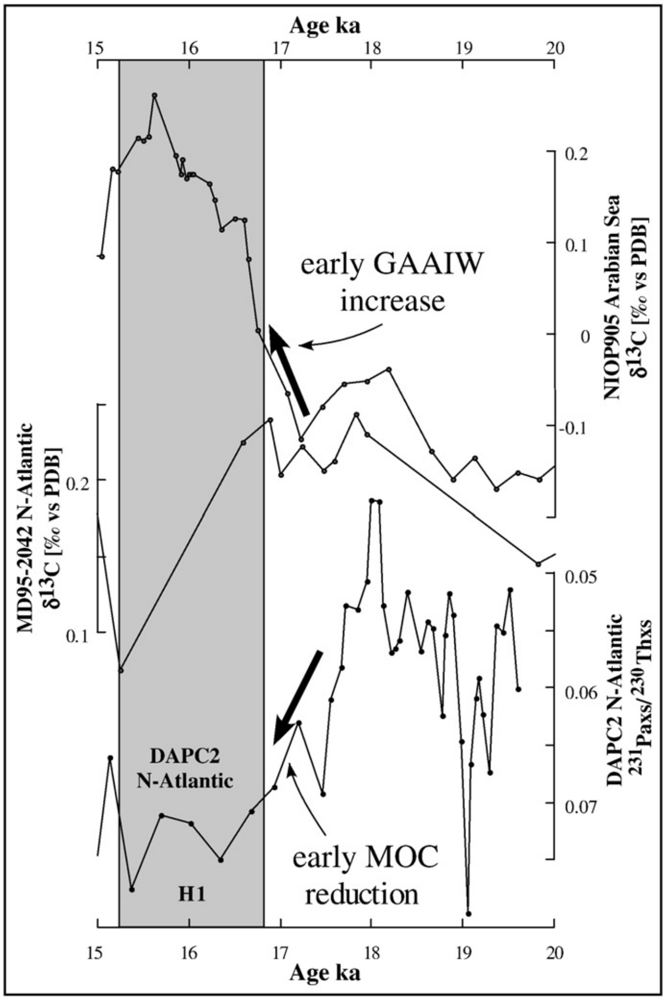

Fig. 6. Arabian Sea Intermediate water circulation around HE1: stable carbon isotope data from Cores NIOP 905 (intermediate depth Arabian Sea) and MD 95-2042 (deep Atlantic Ocean) compared with $^{231}Pa_{xs}/^{230}Th_{xs}$ data (paleocirculation proxy) from Core DAPC2 (North Atlantic Rockall Trough) (Hall et al., 2006). Gray area indicates HE1 (also taken from (Hall et al., 2006)).

experiments for the modern ocean suggest that N-Atlantic MOC variations are inversely related to the strength of GAAIW circulation in the Atlantic sector (Saenko et al., 2003; Sijp and England, 2006). The balance critically depends on the vertical mixing in the ocean well beyond the Atlantic sector. For instance, the intensity of upward mixing of deepwater in the Indian and Pacific Ocean, linking the deep and sub/surface branch of the THC, tends to affect the stability of the overturning circulation in the N-Atlantic (Sijp and England, 2006). Applying these modelling results to the Heinrich-Event time world, repeated expansions of Southern Ocean derived GAAIW may have affected vertical water exchange in the Indian Ocean (Core NIOP 905) and the SW-Pacific (based on recent results (Pahnke and Zahn, 2005)). Thus, synchronicity of intensification of GAAIW and draw down in N-Atlantic MOC (Hall et al., 2006) (Fig. 6) suggests that variations in the balance of southern/northern hemisphere derived intermediate/deepwater masses are important with respect to the tight link of inter-hemispheric millennial time-scale climate change.

4. Concluding remarks

Our study demonstrates that increases in intermediate water flow in the Indian and southwest Pacific Ocean occurred in anti-phase with changes in the N-Atlantic Ocean during Heinrich Events. The occurrence of enhanced temperatures in GAAIW during the most pronounced N-Atlantic cold phases (Fig. 1) could have been significant for the distribution of Earth's energy budget. In general, the present study shows that GAAIW formation is an integral part of the persistent nature of asynchronous millennial time-scale glacial climate change on an inter-hemispheric scale as predicted by modelling experiments (Sijp and England, 2006).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2009.01.037.

References

Adkins, J., Mcintyre, K., Schrag, Daniel P., 2002. The salinity, temperature and d18O of the glacial deep ocean. Science 298, 1769–1773.
Altabet, Mark A., Higginson, Matthew J., Murray, R.W., 2002. The effect of millennial-scale changes in the Arabian Sea denitrification on atmospheric CO2. Nature 415, 159–162.
Blunier, T., Brook, E.J., 2001. Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. Science 291, 109–112.
Blunier, T., Chappellaz, J., Schwander, J., Daellenbach, A., Stauffer, B., Stocker, T.F., Raynaud, D., Jouzel, J., Clausen, H.B., Hammer, C.U., Johnson, S.J., 1998. Asynchrony of Antarctic and Greenland climate change during the last glacial period. Nature (London) 394, 739–743.
Boyle, E., Labeyrie, L., Duplessy, J.-C., 1995. Calcitic foraminiferal data confirmed by cadmium in aragonitic Hoeglundia: application to the last glacial maximum in the northern Indian Ocean. Paleoceanography 10, 881–900.
Charles, C.D., Fairbanks, R.G., 1992. Evidence from Southern Ocean sediments for the effect of North Atlantic deepwater flux on climate. Nature 355, 416–419.
Dansgaard, W., Johnson, J.J., Clausen, B.H., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörndottir, A.E., Jouzel, J., Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature 364, 218–220.
De Ruijter, W.P.M., Ridderinkhof, H., Lutjeharms, J.R.E., 2002. Obersvations of the flow in the Mozambique Channel. Geophys. Res. Lett. 29. doi:10.1029/2001GL013714.
Emery, W.J., Meincke, J., 1986. Global water masses: summary and review. Oceanol. Acta 9, 383–391.
Epica, 2006. One-to-one coupling of glacial climate variability in Greenland and Antarctica. Nature 444, 195–198.
Hall, I.R., Moran, S.B., Zahn, R., Knutz, Paul C., Shen, C.C., Edwards, R.L., 2006. Accelerated drawdown of meridional overturning in the late-glacial Atlantic triggered by transient pre-H event freshwater perturbation. Geophys. Res. Lett. 33. doi:10.1029/2006GL026239.
Ivanochko, T.S., Ganeshram, R.S., Brummer, G.-J.A., Ganssen, G., Jung, S.J.A., Moreton, S.G., Kroon, D., 2005. Variations in tropical convection as an amplifier of global climate change at the millennial scale. Earth Planet. Sci. Lett. 235, 302–314.
Jung, S.J.A., Wassermassenaustausch zwischen NE-Atlantik und Nordmeer während der letzten 300 000/80 000 Jahre im Abbild stabiler O- und C-Isotope. 1996 PhD-thesis. Christian-Albrechts-Universität Kiel, Kiel, p. 104.
Jung, S.J.A., Ganssen, G., Davies, G.R., 2001. Multi-decadal variations in the Early Holocene outflow of Red Sea Water into the Arabian Sea. Paleoceanography 16, 658–668.
Kallel, N., Labeyrie, L., Juillet-Leclerc, A., Duplessy, J.-C., 1988. A deep hydrological front between intermediate and deepwater masses in the glacial Indian Ocean. Nature 333, 651–655.
Keeling, R., Stephens, Britton B., 2001. Antarctic sea ice and the control of Pleistocene climate instability. Paleoceanography 16, 112–131.
Kroopnick, P.M., 1985. The distribution of 13C of SCO2 in the world oceans. Deep-Sea Res. 32, 57–84.
Mccarthy, M.C., Talley, L.D., 1999. Three dimensional isoneutral potential vorticity structure in the Indian Ocean. J. Geophys. Res. 104, 13251–13267.
Nof, D., 2003. The southern ocean's grip on the northward meridional flow. Prog. Oceanogr. 56, 223–247.
Pahnke, K., Zahn, R., 2005. Southern hemisphere water mass conversion linked to North Atlantic climate variability. Science 307, 1741–1746.

Pahnke, K., Zahn, R., Elderfield, H., Schulz, M., 2003. 340,000-year centennial-scale marine record of southern hemisphere climatic oscillation. Science 301, 948–952.
Pahnke, K., Goldstein, S., Hemming, S., 2008. Abrupt changes in Antarctic Intermediate Water circulation over the past 25,000 years. Nat. GeoSci 1, 870–874. doi:10.1038/ngeo1360.
Peacock, S., Maltrud, M., 2006. Transit-time distributions in a global ocean model. J. Phys. Oceanogr. 36, 474–495.
Prasanna Kumar, S., Prasad, T.G., 1999. Formation and spreading of Arabian Sea high-salinity water mass. J. Geophys. Res. 104, 1455–1464.
Saenko, O.A., Weaver, Andrew J., Gregory, J.M., 2003. On the link between two modes of the ocean thermohaline circulation and the formation of global scale water masses. J. Climate 16, 2797–2801.
Saher, M., Jung, S.J.A., Elderfield, H., Greaves, M., Kroon, D., 2007. Western Arabian Sea SSTs during the last deglaciation. Paleoceanography 22. doi:10.1029/2006PA001292.
Sarnthein, M., Winn, K., Jung, S.J.A., Duplessy, J.-C., Labeyrie, L., Erlenkeuser, H., Ganssen, G., 1994. Changes in east Atlantic deepwater circulation over the last 30,000 years: eight time slice reconstructions. Paleoceanography 9, 209–267.
Sarnthein, M., Stattegger, K., Dreger, D., Erlenkeuser, H., Grootes, P., Haupt, B., Jung, S., Kiefer, T., Kuhnt, W., Pflaumann, U., Schaefer-Neth, Ch., Schultz, H., Schultz, M., Seidov, D., Simstich, J., Van-Kreveld, S., Vogelsang, E., Voelker, A., Weinelt, M., 2001. Fundamental modes and abrupt changes in Northern Atlantic circulation and climate over the last 60 ky; concepts, reconstruction and numerical modeling. in: The Northern North Atlantic; a Changing Environment. Schaefer, P., Ritzrau, W., Schlueter, M., Thiede, J. (editor), Springer. Federal Republic of Germany, Berlin, pp. 365–410.
Schmittner, A., Galbraith, E.D., Hostetler, S.W., Pedersen, T., 2007. Large fluctuations of dissolved oxygen in the Indian and Pacifc Oceans during Dansgaard–Oeschger oscillations caused by variations of North Atlantic Deep Water subduction. Paleoceanography 22. doi:10.1029/2006PA001384.
Schulz, H., Von Rad, U., Erlenkeuser, H., 1998. Correlation between Arabian Sea and Greenland climate oscillation of the past 110,000 years. Nature 393, 54–57.
Shackleton, N.J., Hall, Mike A., Vincent, E., 2000. Phase relationships between millennial-scale events 64,000–24,000 years ago. Paleoceanography 15, 565–569.
Shackleton, N.J., Fairbanks, R.G., Chiu, T.-C., Parrenin, F., 2004. Absolute calibration of the Greenland time scale: implications for Antarctic time scales and for $D^{14}C$. Quat. Sci. Rev. 23, 1513–1522.
Shapiro, G.I., Meschanov, S.L., 1991. Distribution and spreading of Red Sea Water and salt lens formation in the northwest Indian Ocean. Deep-Sea Res. 38, 21–34.
Siddall, M., Rohling, E.J., Almogi Labin, A., Hemleben, C., Meischner, D., Schmelzer, I., Smeed, D.A., 2003. Sea-level fluctuations during the last glacial cycle. Nature 423, 853–858.
Sijp, W.P., England, M.H., 2006. Sensitivity if the Atlantic thermohaline circulation and its stability to basin-scale variations in vertical mixing. J. Climate 19, 5467–5478.
Sloyan, B.M., Rintoul, S.R., 2001. Circulation, renewal and modification of Antarctic Mode and Intermediate Water. J. Phys. Oceanogr. 31, 1005–1030.
Stott, L.D., Timmermann, A., Thunell, R.C., 2007. Southern Hemisphere and Deep-Sea Warming Led Deglacial Atmospheric CO2 Rise and Tropical Warming Science. 10.1126/science.1143791.
Vidal, L., Labeyrie, L., Cortijo, E., Arnold, M., Duplessy, J.C., Michel, E., Becqué, S., Van Weering, T.C.E., 1997. Evidence for changes in the North Atlantic Deep Water linked to meltwater surges during the Heinrich events. Earth Planet. Sci. Lett. 146, 13–27.
Waelbroeck, C., Levi, C., Duplessy, J.C., Labeyrie, L., Michel, E., Cortijo, E., Bassinot, F., Guichard, F., 2006. Distant origin of circulation changes in the Indian Ocean during the last deglaciation. Earth Planet. Sci. Lett. 243, 244–251.
Waugh, D.W., Hall, T.M., Haine, T.W.N., 2003. Relationships among tracer ages. J. Geophys. Res. 108. doi:10.1029/2002JC001325.