Surface and deep-water hydrography on Gardar Drift (Iceland Basin) during the last interglacial period

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1. Introduction

The climate of the last interglacial period, corresponding to Marine Isotope Stage (MIS) 5e, was slightly warmer and sea level was several meters higher than today (Overpeck et al., 2006; Jansen et al., 2007; Rohling et al., 2008). Although orbital parameters differed, MIS 5e is commonly used for comparison to the Holocene and for providing a reference of interglacial climate variability in the absence of anthropogenic forcing. A major shortcoming for the study of the LIG is there is yet no complete, undisturbed section of the LIG recovered in Greenland (North Greenland Ice Core Project Members, 2004). Drilling has now begun in northwestern Greenland with the goal of recovering a complete ice core record of the last interglacial (NEEM – North Greenland Eemian Ice Drilling; http://neem.ku.dk/). An important challenge for paleoceanographers is to identify complementary marine sections with sufficiently high sedimentation rates for comparison with the anticipated NEEM ice core.

Here we report on an expanded section of the last interglacial period recovered on the Gardar Drift south of Iceland (Fig. 1). A unique feature of Integrated Ocean Drilling Program (IODP) Site U1304 is that it possesses an expanded section of the “MIS 5e isotopic plateau” (128 to 116 ka) (Shackleton et al., 2003) and MIS 5d (116 to 105 ka). The sediment deposited in this period includes the intermittent occurrence of laminated diatom mats (LDM) and oozes (LDO) (Expedition 303 Scientists, 2006), which were rapidly deposited at the North Subarctic Front (NSAF) (Bodén and Backman, 1996). The high tensile strength of the LDM/LDO suppresses benthic activity and hinders bioturbation in the underlying sediment, thereby offering a rare opportunity to study the last interglacial period and its demise into substage 5d at ultra high resolution (i.e., multi-decadal to centennial time scales). Furthermore, the water depth of Site U1304 at 3076 m extends the depth range of previous reconstructions of bathymetric \(^{13}C\) from cores taken from North Atlantic sediment drifts (Oppo et al., 1997).

We measured stable isotope ratios of multiple species of foraminifera to reconstruct changes in surface and deep-water hydrography...
for the period from MIS 6 to substage 5d. Planktonic δ¹⁸O of foraminifera from Gardar Sediment Drift record the nature of surface flow to the Nordic Seas via the North Atlantic Current, whereas benthic δ¹³C monitors the ventilation of deep water. By comparing our planktonic and benthic isotope records with previously published paleocurrent reconstruction of flow speed, changes using sortable silt (SS, the mean grain size of the 10–63 µm terrigenous sediment sub-fraction), we examine the timing and linkages between surface water inflow and deep-water outflow over the Iceland–Scotland Ridge during the LIG.

2. Site locations and hydrography

The Gardar Drift is an elongated contourite deposited along the eastern flank of the Reykjanes Ridge. It was formed by the interaction of Iceland Scotland Overflow Water (ISOW), flowing as a Deep Western Boundary Current (DWBC), and local topography (Bianchi and McCave, 2000). The drift deposit is oriented NE–SW and extends for about 1100 km, increasing in water depth from ~1400 m water depth in the NE to >3000 m in the SW near the Charlie Gibbs Fracture Zone (CGFZ) (Fig. 1) (Bianchi and McCave, 2000).
The Iceland–Scotland ridge is the site of one of the overflows of water from the Nordic Seas to the North Atlantic, the other being Denmark Strait (Fig. 1). ISOW forms through convection in the Norwegian Greenland Sea via cooling of warm surface waters transported north by the North Atlantic Current (NAC). ISOW entrains ambient water, mainly Labrador Sea Water (LSW), to form a descending plume that transports approximately 6 Sv (1 Sv = 10^6 m^3 s^-1) of water through the CGFZ (Smethie et al., 2007). Along with Denmark Strait Overflow Water (DSOW) and LSW, CGFZ water contributes an important component of North Atlantic Deep Water (NADW) that constitutes the lower limb of the Atlantic Meridional Overturning Circulation (AMOC) (Quadfasel and Kase, 2007).

Found below ISOW on the southern Gardar Drift is Lower Deep Water (LDW), which is sourced from the Southern Ocean as reflected by its high silica content (McCartney, 1992; Reid, 1994). During the last glacial period, the source area for deep-water formation moved south of the Greenland–Scotland Ridge and NADW was replaced by a shallower water mass known as Glacial North Atlantic Intermediate Water (GNAIW) above ∼2000 m water depth (Oppo and Lehman, 1993; Curry and Oppo, 2005). Below 2000 m, deep water in the North Atlantic was dominated by a water mass originating in the Southern Ocean. Previous studies have shown the Gardar Drift preserves a detailed record of variations in ISOW (Channell et al., 1998; Bianchi and McCave, 1999; Bianchi and McCave, 2000; McCave and Hall, 2006).

We studied Site U1304 located on the southern edge of the Gardar Drift in 3082 m water depth close to CGFZ (Fig. 1) (Channell et al., 2006). Site U1304 is compared with the records from two other sites from the same drift deposit. Site 983 is positioned on the northern part of the drift in 1983 m water depth. It is bathed by a mixture of ISOW and Labrador Sea Water (LSW) today (Schmitz and McCartney, 1993; Reid, 1994). Kasten core NEAP-18K is located ∼210 km to the NW of Site U1304 and in slightly deeper water (3275 m) (Hall et al., 1998) (Fig. 1). Both sites U1304 and NEAP-18K are influenced today mostly by ISOW with a minor component of LSW. During the last glaciation, Site U1304 and NEAP-18K were bathed by LSW sourced from the Southern Ocean, whereas Site 983 was positioned near the boundary of GNAIW and LSW (Oppo and Lehman, 1993).

3. Methods

The composite section of Site U1304 was sampled at a constant 5-cm spacing between 24.52 and 15.47 mcd, corresponding to the MIS 6 through MIS 5d interval. The last interglacial and transition to MIS 5d is contained in Core 1304A-2H-1 (Fig. 2). The mean sedimentation rate for MIS 5e and 5d is 40 cm ka^-1, which results in an average sampling frequency of 125 years.

Stable oxygen (δ^18O) and carbon (δ^13C) isotope ratios were measured on three species of planktonic foraminifera (Globigerina bulloides, Neogloboquadrina incompta (formerly Neogloboquadrina pachyderma dextral), and Glaborotalia inflata) and the epi-benthic foraminifera Cibicides wuellerstorfi. All isotope measurements were made using a Finnigan-MAT 252 isotope ratio mass spectrometer coupled with a Kiel III carbonate preparation device, and are reported in standard delta notation relative to Vienna Pee Dee Belemnite (VPDB) using NBS-19 for calibration. The estimated analytical error is better than ± 0.1‰ for both δ^18O and δ^13C.

Sediment lightness was measured at 2-cm intervals shortly after cores were split using a Minolta CM1500 Spectrophotometer (Expedition 303 Scientists, 2006). Weight percent CaCO₂ was determined using a UIC (Coulometrics) 5011 CO₂ coulometer coupled with an AutoMateFX carbonate prep system. Magnetic susceptibility was measured on u-channel subsamples at 1-cm resolution using a custom-built instrument in the paleomagnetic laboratory at the University of Florida (Thomas et al., 2003).

4. Results

4.1. Oxygen isotopes

Termination II, the glacial to interglacial transition from MIS 6 to 5, is marked by a rapid decrease in δ^18O in all species of foraminifera at ∼22.7 mcd (Fig. 3). Following this event, benthic δ^18O (C. wuellerstorfi) reveals a broad plateau of unchanged values for 4.9 m from 22.6 to 17.7 mcd during MIS 5e (Fig. 3). Benthic δ^18O values average 2.69 ± 0.08‰ (n = 86) and variation is within analytical error. Greater δ^18O is expressed in planktonic δ^18O during the plateau interval. The duration of minimum δ^18O during MIS 5e varies among planktonic species. The δ^18O minimum is briefest in G. bulloides, slightly longer in G. inflata, and longest-lived in N. pachyderma (dex). A second δ^18O minimum occurs at the substage 5e/5d boundary in G. bulloides and G. inflata only. All planktonic δ^18O records increase during MIS 5d towards a distinct maximum at 16 mcd.

4.2. Carbon isotopes

Benthic δ^13C ranges from −0.4 to 1.2‰. No significant change occurs in benthic δ^13C across Termination II as δ^13C remains low during the early part of MIS 5e (Fig. 3). Benthic δ^13C increases at 21.3 mcd and remains relatively high until the end of the MIS 5e plateau (116 ka) when δ^13C shows two minima near the MIS 5e/5d transition. The lows in benthic δ^13C at the beginning of MIS 5e and near the substage 5e/5d boundary coincide with minima in the δ^18O of G. bulloides and G. inflata (Fig. 3). Benthic δ^13C increases to maximum values of 1.2% at 15.5 mcd in MIS 5d.

4.3. Lithostratigraphy

MIS 6 sediment is composed of gray clay with wt.% CaCO₂ averaging ~20% and high, but variable, magnetic susceptibility (Fig. 3). A large peak in ice-rafted detritus (IRD) occurs at 22.5 mcd on Termination II, marked by carbonate content approaching 0%. Following this event (Heinrich Event 11) (Heinrich, 1988), wt.% CaCO₂ rises to 39% at 22 mcd and then decreases to 32% at 21.5 mcd. The earliest part of MIS 5e is generally marked by darker sediment with higher magnetic susceptibility and lower carbonate content than the latter part of MIS 5e. Lightness and CaCO₂ content increase and magnetic susceptibility decreases from 22 to 20 mcd with another step at 19 mcd, reaching a maximum wt.% CaCO₂ value of 64%. Sediment lightness and CaCO₂ remain high and magnetic susceptibility low until the end of the MIS 5e plateau (17.7 mcd). During the transition to MIS 5d, CaCO₂ content declines and magnetic susceptibility increases, reaching a peak at ~16 mcd corresponding to event C24 (McManus et al., 1994). Diatom layers become common in the section at 20.5 mcd (base of 1308A-2H-4; Fig. 2).

4.4. Chronology and sedimentation rates

We adopt the definition of the CAPE Project Members (2006) who took the LIG to represent the interval of minimum ice volume when benthic δ^18O values were low and relatively constant during the MIS 5e plateau. We note, however, that the terrestrial record of the last interglacial (i.e., Eemian in Europe) differs in timing compared to the marine record (Shackleton et al., 2002, 2003). Shackleton et al. (2002, 2003) developed a radiometric time scale for the LIG that is independent of astronomical calibration. They estimated an age of 128 ka for the start of the MIS 5e plateau, and an age of 116 ka for the end of the plateau (Shackleton et al., 2002, 2003). We adopt these calibration points and use another at the peak of MIS 5d (107 ka) corresponding to C24 (McManus et al., 1994) or Greenland Stadial (GS) 24 (Rouesse et al., 2006). Sedimentation rates at Site U1304 average 40 cm ka^-1 during the MIS 5e plateau interval.
5. Discussion

5.1. Comparison with other records

We compare the record from Site U1304 with previously published results from two sites on Gardar Drift: ODP Site 983 (Channell et al., 1997) and NEAP-18K (Hall et al., 1998).

Oxygen isotopes of *Cibicidoides* and *G. bulloides* at Site 983 show uniformly low values from 15.7 to 13.1 mcd. Sedimentation rates average 17 cm ka$^{-1}$ during the MIS 5e plateau. Similar to Site U1304, the early part of the LIG is marked by lower carbonate content than the latter part. The water depth of Site 983 (1983 m) is more than a km shallower than Site U1304 (3082 m), yet the benthic $\delta^{13}C$ record shows a similar minimum at Termination II and into the earliest part of the MIS 5e plateau (Fig. 4). Based on a constant sedimentation rate between the start and end of the MIS 5e plateau at Site U1304, we estimate this low- $\delta^{13}C$ water mass persisted for $\sim 3$ ka into the LIG until $\sim 124.5$ ka. A similar calculation for Site 983 yields a slightly shorter duration lasting until $\sim 126$ ka.

The bottom of core NEAP-18K just reached Termination II as Heinrich event 11 occurs at the base of the record (Chapman and Shackleton, 1999). The MIS 5e plateau at NEAP-18K spans 80 cm with sedimentation rate averaging 6.6 cm ka$^{-1}$ (Fig. 5). The $\delta^{18}O$ record of *G. bulloides* at NEAP-18K shows the same pattern as Site U1304, with lowest values at the beginning of the MIS 5e plateau associated with peak summer boreal insolation (Fig. 6A,B).

The benthic $\delta^{13}C$ record at NEAP-18K shows similar trends as those at Site U1304, but NEAP-18K has consistently higher values throughout MIS 5e and 5d (Fig. 6C). This is unlikely to be the result of the two sites being bathed by different water masses because they are only 210 km apart and separated by $\sim 200$ m water depth. The Site U1304 benthic $\delta^{13}C$ record shows several minima (with values approaching $-0.5$‰) that are not apparent at NEAP-18K. The lower sedimentation rate ($\sim 6$ cm ka$^{-1}$) and greater mixing by bioturbation at NEAP-18K may filter the short-term $\delta^{13}C$ variations, but this shouldn’t result in a constant offset between the two records. Alternatively, low benthic $\delta^{13}C$ values at Site U1304 may reflect a phytodetritus effect related to the increased flux of organic matter to the sediment-water interface. Mackensen et al. (1993) proposed that a high flux of organic matter to the sediment-water interface can create a phytodetritus layer with low $\delta^{13}C$ derived from the oxidation of $13C$-depleted organic matter. Epifaunal benthic foraminifera, such as *C. wuellerstorfi*, living in this microhabitat might record $\delta^{13}C$ values lower than ambient bottom water. Organic matter associated with increased diatom productivity is not likely the cause for the low benthic $\delta^{13}C$ values in the early LIG, however, because the common occurrence of diatom ooze does not begin until $\sim 20.5$ mcd, which is well above the interval of lowest $\delta^{13}C$ values (Fig. 3).

The benthic $\delta^{13}C$ records at Sites 983 and U1304 show nearly identical patterns across Termination II, favoring the interpretation that low benthic $\delta^{13}C$ reflects variations in deep-water ventilation. Furthermore, the similarity of the Site U1304 benthic $\delta^{13}C$ and the SS...
near-bottom flow speed variations at NEAP-18K suggest both are recording circulation changes (Fig. 6D) (Hall et al., 1998). Each of the minima in benthic δ¹³C at Site U1304 coincides with a decrease in SS indicating reduced vigor of deep water on the southern Gardar Drift. Unlike nutrient related hydrographic proxies such as benthic δ¹³C, SS is a physical proxy of relative current speed that is unaffected by biological processes. At NEAP-18K, SS suggests that flow speeds are lowest during the earliest part of the MIS 5e plateau and at the transition from MIS 5e to 5d (Figs. 5 and 6D). The SS record was compared to a very similar record in the N. American Basin on Bermuda Rise at 4462 m by Hall et al. (1998), They noted that the T-II/early 5e slow speeds corresponded to the nutrient-rich (high Cd/Ca) water of southern origin identified by Adkins et al. (1997). Thus the coordinated behavior of water masses and their flow speed was likely both ocean-wide and controlled from the Southern Ocean source.

5.2. Bathymetric δ¹³C gradients

Following the lead of Oppo et al. (1997), we constructed bathymetric δ¹³C gradients for several time slices including MIS 6 (at maximum benthic δ¹⁸O value), Termination II, and early and late MIS5e (Fig. 7). Oppo et al. (1997) used sites spanning a depth range from 1451 to 2658 m for their reconstruction based mainly on cores from the Bjorn Drift. To these data we add IODP Site U1304 (3076 m) and 983 (1983 m) from Gardar Drift and Site 982 (1145 m) from the Rockhall Plateau.

The carbon isotopic gradient during MIS 6 was very similar to the last glacial period with high values above 2000 m and low values below (Fig. 7). This pattern reflects the presence of GNAIW at intermediate depths and southern-sourced water below ∼2000 m (Oppo and Lehman, 1993). Carbon isotopic values decreased through-out the water column from MIS 6 to Termination II with the most pronounced change occurring at intermediate depth. The bathymetric δ¹³C gradient displays an S-shaped pattern with a distinct minimum at intermediate depth (∼1500–1700 m), higher values between ∼2000 and 2700 m, and another low value below 3000 m. The pattern of the bathymetric δ¹³C gradient remains unchanged into the earliest part of MIS 5e (Fig. 7). During later MIS 5e, the benthic δ¹³C gradient assumes a Holocene-like pattern with high δ¹³C throughout the upper 2500 m of the water column.

Many other studies have reported a nutrient-rich water mass in the North Atlantic during Termination II (Zahn et al., 1987; Oppo and Lehman, 1993; Adkins et al., 1997; Oppo et al., 1997; Lototskaya and Ganssen, 1999; Oppo et al., 2001; Oppo et al, 2006; Skinner and Shackleton, 2006). In some cores, the low carbon isotopic values of Termination II extend into the early part of the LIG resulting in what
Skinner and Shackleton (2006) describe as a drawn out appearance to the deglaciation where benthic $\delta^{13}C$ lags behind the sharper increases in temperature and $\delta^{18}O$. At intermediate Site 982 on Rockall Plateau at 1145 m water depth, benthic carbon isotope minima are a common feature of Pleistocene deglaciations, including Termination II where the $\delta^{13}C$ depletion extends into MIS 5e (Venz et al., 1999).

At Site U1304, there was relatively little change in benthic $\delta^{13}C$ across Termination II from MIS 6 to early MIS 5e (Fig. 3). It is likely that Site U1304 continued to be bathed by southern sourced water through Termination II and early MIS 5e. The SS record at NEAP-18K indicates relatively weak flow below ~3000 m on the southern Gardar Drift during the early part of the MIS5e plateau (Figs. 5 and 6). Slightly higher $\delta^{13}C$ values occur between ~2000 and 2700 m in the depth range occupied today by ISOW on Gardar and Bjorn Drifts (Bianchi and McCave, 2000), suggesting that ISOW may have formed during Termination II and early MIS 5e but did not penetrate to depths of 3000 m.

GNAIW, which formed in the subpolar North Atlantic south of Iceland during MIS 6, ceased being produced during Termination II and the intermediate-depth North Atlantic was bathed by a low-$\delta^{13}C$ water mass. Previously suggested sources for this low-$\delta^{13}C$ water mass include nutrient-rich water sourced from the Southern Ocean or low-$\delta^{13}C$ water from the Nordic Seas (Oppo et al., 1997; Raymo et al., 2004).

Intermediate depths in the North Atlantic between ~800 and ~2000 m are influenced today by three principal water masses: LSW and Antarctic Intermediate Water (AAIW) (Kawase and Sarmiento, 1986). LSW is the dominant water mass between ~1000 and ~1600 m, but it was not formed during the LIG (Hillaire-Marcel et al., 2001). Similarly, MOW, which lies between ~800 and ~1000 m, was reduced during Termination II as marked by a prominent benthic $\delta^{13}C$ minimum in cores off the Strait of Gibraltar (Zahn et al., 1987).

MOW was also likely reduced during early MIS 5e as this was the time of deposition of sapropel S5 indicating anoxic to euxinic deep water conditions in the Mediterranean (Rohling et al., 2006). If GNAIW, LSW, and MOW were greatly reduced or curtailed during Termination II and early 5e, then intermediate waters from the Southern Ocean could have penetrated farther into the North Atlantic. AAIW occupies levels shallower than 800 m today in the North Atlantic and is difficult to trace north of 25°. Other studies have suggested that AAIW was volumetrically more important during the past, penetrating to as high as 60° in the North Atlantic during the last termination (Rickaby and Elderfield, 2005).

If the low $\delta^{13}C$-water at intermediate depth in the North Atlantic has a Southern Ocean origin, then it may be related to carbon isotopic minima found elsewhere in the oceans. For example, Spero and Lea (2002) described the occurrence of a carbon isotope minimum event at Terminations I and II in deep-dwelling planktonic foraminifera in the equatorial Pacific. They suggested its origin was low-$\delta^{13}C$ water from the Southern Ocean that was transported to the base of the tropical thermocline by AAIW. In this case, the mid-depth low in $\delta^{13}C$ at Termination II in the North Atlantic may partly reflect the deglacial escape of old carbon and nutrients that were stored in bottom waters during the penultimate glaciation.

Alternatively, the low-$\delta^{13}C$ water in the intermediate-depth North Atlantic may have originated from the Nordic Seas (Bauch et al., 2000). Raymo et al. (2004) showed that the high-$\delta^{13}C$ water that forms in the Nordic Seas today was unusual in the past, and only occurred during extreme interglacials of the late Pleistocene. Our bathymetric $\delta^{13}C$ profile for Termination II and early MIS 5e is similar to their glacial-interglacial profiles between 0.6 and 1.8 Ma, which show a strong mid-depth $\delta^{13}C$ minimum. They concluded that low-$\delta^{13}C$, mid-depth water originated from the Nordic Seas, perhaps from water formed by brine
rejection under sea ice (Dokken and Jansen, 1999; Bauch et al., 2000). Low benthic foraminiferal δ13C has been noted in cores from the Norwegian Sea during the penultimate deglaciation and into the beginning of the LIG (Duplessy and Shackleton, 1985; Oppo and Lehman, 1995; Fronval and Jansen, 1997; Bauch et al., 2000).

5.3. Surface-deep connection

Planktonic δ18O of foraminifera from Gardar Drift records temperature and salinity conditions of subpolar surface waters, which flow into the Nordic Seas via the North Atlantic Current. Minimum δ18O of

Fig. 6. A. Insolation anomaly relative to today at 65°N at boreal summer solstice. B. δ18O of G. bulloides at Site U1304 (black) and NEAP-18K (red) (Chapman and Shackleton, 1999); C. Benthic δ13C at Sites U1304 (blue line with bold 5-point running mean) and NEAP-18K (red line with bold 5-point mean); D. Benthic δ13C at Site U1304 (blue) and sortable silt (red) at NEAP-18K (Hall et al., 1998). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
G. bulboides and G. inflata from ~128 to 126 ka indicates warming and/or reduced salinity of surface waters associated with peak boreal summer insolation (Fig. 6A,B). This occurs approximately at the same time as the low benthic δ13C at Sites U1304 and 983 and low SS values at NEAP-18K. The peak summer insolation during early MIS 5e may have resulted in increased melting of continental ice, thereby increasing fresh water fluxes and decreasing surface water salinity in source areas for deep-water formation in the Nordic Seas. The Greenland ice sheet is particularly sensitive to warm, early summer conditions and likely had a negative mass budget during the earliest LIG (Otto-Bliesner et al., 2006).

We suggest that low-δ13C water and slow current speed on Gardar Drift at 3–3.3 km during the early part of the LIG was the result of increased melt water fluxes to the Nordic Seas during peak boreal summer insolation, which decreased the strength and/or density of overflow to the North Atlantic. This left the slowly circulating SSW in place until a strengthened/denser ISOW was able to replace it later in 5e. Support for this interpretation comes from a comparison of the benthic δ13C of Site U1304 and salinity estimated from dinocysts off southern Greenland (Fig. 8) (de Vernal and Hillaire-Marcel, 2008). The early part of the LIG was marked by generally lower and more variable surface salinity conditions, resulting from high rates of melt water flux from the retreating Greenland ice sheet. In the Norwegian Sea, the earliest part of the LIG was marked by significant freshwater and IRD inputs (van Nieuwenhove et al., 2008; Bauch and Erlenkeuser, 2008). This period corresponds to the low benthic δ13C at Site U1304 and slow current speed at NEAP-18K.

Modeling studies suggest that orbital parameters during the last interglacial favored a high-index state of the North Atlantic Oscillation (NAO) (Felis et al., 2004). Less vigorous ISOW due to larger admixture of fresher LSW has been associated with positive phases of the NAO during the late Holocene (Boessenkool et al., 2007). If peak boreal summer insolation during the early LIG favored a persistent positive NAO, then this state may have contributed to weak ISOW at 3000 m inferred from the deep Gardar Drift.

Higher and more stable salinity conditions prevailed during the latter part of MIS 5e beginning ~124 ka (Fig. 8) (Hillaire-Marcel et al., 2001; de Vernal and Hillaire-Marcel, 2008). At the same time, benthic δ13C at Site U1304 and SS at NEAP-18K increased and remained high throughout the remainder of MIS 5e until 117 ka, indicating penetration of ISOW to depths of >3.3 km. Near the end of the MIS 5e plateau at 117 ka, salinity off south Greenland decreased and became more variable at the same time as benthic δ13C and SS decreased with the lowest values occurring at 113 ka near the transition from MIS 5e to 5d. These results suggest a weakening of ISOW on the deep Gardar Drift in response to lowered surface salinity in the Labrador, Irminger and Nordic Seas.

Other studies have also reported a brief, but pronounced reduction in NADW at the end of MIS 5e and a greater proportion of SSW in the deep North Atlantic (Adkins et al., 1997; Lehman et al., 2002). In contrast, McManus et al. (2002) inferred enhanced ventilation at intermediate Site 980 and increased heat transport to the subpolar North Atlantic with glacial initiation (McManus et al., 2002). Our results are consistent with both of these observations because whereas benthic δ13C increased at intermediate depth (Fig. 4), benthic δ13C and SS decreased below 3000 m on Gardar Drift (Fig. 6D). These data can be explained by a shoaling of the boundary between intermediate and deep waters on the Gardar Drift such that the contribution and vigor of ISOW was reduced in deep-water sites but an ISOW influence persisted at intermediate depth.

Both chemical and physical ventilation tracers suggest a deepening and strengthening of ISOW on the deep Gardar Drift beginning at ~109 ka (Hall et al., 1998). At this time, salinity off south Greenland increased and remained high and steady (Fig. 8). Even though climate continued to deteriorate during MIS 5d, both chemical and physical ventilation tracers suggest a deepening and strengthening of ISOW on the deep Gardar Drift (Hall et al., 1998). For example, there is little δ13C difference between Sites 983 and U1304 with both sites displaying high values of ~1‰, similar to the modern hydrography (Figs. 3, 4).
6. Summary and significance

We found evidence for low-δ13C water throughout much of the water column during Termination II and the earliest part of the LIG on Gardar Drift. Minimum values of benthic δ13C occurred at intermediate depths (~1500–2000 m) and below 3000 m. Sortable silt mean size at NEAP-18K (3275 m) was low during the early part of MIS 5e indicating relatively slow circulation from ~128 to 124.5 ka. The low-δ13C water and slow current speed coincided with minimum planktonic δ18O on Gardar Drift and low salinity surface conditions off southern Greenland (de Vernal and Hillaire-Marcel, 2008). We suggest that low-δ13C water and slow current speed on deep Gardar Drift was related to increased meltwater fluxes to the Labrador and Nordic Seas during peak boreal summer insolation, which decreased the strength and/or density of overflow to the North Atlantic. The resumption of strong, well-ventilated ISOW on Gardar Drift was delayed until ~124 ka. The lagged response of ISOW on Termination II may have had an effect on AMOC, but because ISOW provides only one component of NADW, additional information is needed on the response of other contributors such as DSW and LSW.

Most computer simulations of climate forced by enhanced greenhouse gas concentrations predict that AMOC will weaken, perhaps by as much as 30% by the end of this century, as the Nordic Seas become fresher and warmer (Manabe and Stouffer, 1999; Rahmstorf and Ganopolski, 1999; Rahmstorf, 2003; Delworth and Dixon, 2006; Dickson et al., 2002). Although future greenhouse gas forcing will be different than the insolation forcing of the LIG, our findings indicate that circulation on the Gardar Drift was weaker during the earliest part of the LIG when climate was warmer than present and the Greenland ice sheet was retreating (Otto-Bislersen et al., 2006).

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