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Centennial to millennial scale Holocene climate-deep water linkage in the North Atlantic☆

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Abstract

The stability of the Earth's climate is strongly linked to the steadiness of the atmospheric and oceanic transport of heat from low to high latitudes. High resolution Holocene sedimentary records from the subpolar North Atlantic demonstrate a persistent link between centennial to millennial scale fluctuations in the flow speed of Iceland-Scotland Overflow Water inferred from granulometric proxy data and both the surface North Atlantic Current component of the meridional overturning circulation (MOC) and published Fennoscandian atmospheric temperature variability. However, these data also highlight the difficulties associated with the interpretation of geochemical and sedimentological deep water circulation proxies as they do not provide a wholly consistent picture. The similarity between surface and deep ocean $\delta^{13}C$ records suggests a preformed component in the deep ocean $\delta^{13}C$ signal. On the other hand, the sedimentological results display a strong linkage to changing conditions in the overlying surface ocean waters, suggesting this proxy better reflects the activity of the MOC at least during the Holocene of this region. The most widespread oceanic perturbation coincides with an interval of possibly global climatic deterioration around 2700 years ago. These results firmly establish deep water production in the Nordic Seas as a key component in the assortment of variables affecting climate during the Holocene.

1. Introduction

The role of the MOC in dramatic, and abrupt climate variability during the last ice age is well documented (Clark et al., 2002 and references therein). Increasingly, Holocene climate proxy records indicate the presence of millennial and centennial scale climatic events which are subdued compared to their glacial counterparts (e.g. Bianchi and McCave, 1999; deMenocal et al., 2000; Giraudeau et al., 2000; Bond et al., 2001; Haug et al., 2001; Oppo et al., 2003; Risebrobakken et al., 2003). However, the evidence for Holocene variability in the influx of bottom waters from the Nordic Seas into the North Atlantic is thus far scant and its relationship to surface ocean climate is still unclear (Bianchi and McCave, 1999; Chapman and Shackleton, 2000; Giraudeau et al., 2000; Oppo et al., 2003). The problem is compounded by existing difficulties in the interpretation of granulometric reconstructions of deep ocean flow speeds due to differences in both the analytical methods employed and the possibility that modest deep water flow instabilities only produce subtle sedimentological responses that may not be present, at least in the same form, a relatively short distance away. Furthermore, geochemical proxies may be unable to differentiate between changes in the preformed chemistry and variations in the ventilation rate of deep waters (Duplessy et al., 1988). Here, some of the challenges of Holocene palaeoceanography are addressed by providing well-dated, mostly continuous, multi-proxy records of surface and deep ocean circulation changes from an individual core.

2. Material and methods

Our climate records have been obtained from kasten core NEAP4K recovered from the rapidly deposited sediments of the Björn Drift, northern Iceland Basin

☆Table 1 available in the online version of this article, doi:10.1016/j.quascirev.2004.04.004

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(61° 29.91′ N, 24° 10.33′, 1627 m water depth, Fig. 1), a location that is ideally positioned to record both fluctuations in the intensity of the North Atlantic Current (NAC) and the deep Iceland Scotland Overflow Water (ISOW) component of the MOC (Bianchi and McCave, 2000). The chronology for NEAP4K is based on a series of thirteen ^{14}C dates (see Fig. 2a; a list of the radiocarbon dates is given in Table 1 of the online version of this article) determined from monospecific samples of the planktic foraminifera *Globigerina bulloides*. Radiocarbon ages were corrected to calendar years B.P. (Stuiver et al., 1998). The average sedimentation rate for core NEAP4K is $\sim$18 cm ka^{-1}. The core was sampled every 1 cm (or about 50 years).

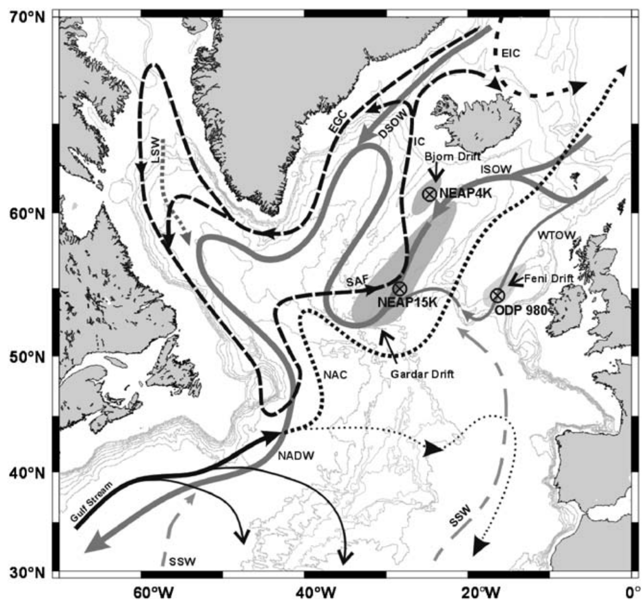

Fig. 1. Location of study area with a generalized circulation scheme [after Mauritzen (1996)]. The location of NEAP4K on Björn Drift and ODP Site 980 on Feni Drift is shown. Abbreviations are: NAC, North Atlantic Current; IC, Irminger Current; EGC, East Greenland Current; EIC, East Iceland Current; SAF, Subarctic Front; ISOW, Iceland Scotland Overflow Water; WTOW, Wyville-Thomson Overflow Water; DSOW, Denmark Strait Overflow Water; LSW, Labrador Sea Water; NADW, North Atlantic Deep Water; SSW, Southern Source Water. Björn Drift is an $\sim$300 km-long sedimentary body presently lying under the main pathway of ISOW that flows as a southwesterly deep western boundary current which closely hugs the seabed topography (Bianchi and McCave, 2000). ISOW enters the Iceland Basin across the Iceland-Scotland Ridge, flowing mainly through the Faeroe Bank Channel. As it does so, it also entrains overlying water masses, of which the most important is LSW (Harvey and Theodorou, 1986). The intensity of the overflow upstream of the sills is strongly influenced by the surface water circulation of the subpolar North Atlantic that in turn is dominated by the poleward advection of warm waters in the NAC (van Aken and Becker, 1996) — the northward extension of the Gulf Stream. The boundary between the subpolar and warm Atlantic waters is roughly defined by the position of the southwest-northeast trending SAF. The NAC is climatically important as it is a major source of heat and moisture to the atmosphere, which modulates the temperate climate of northwestern Europe. Furthermore, its involvement in the convective activity of the Arctic/Nordic Seas that leads to the formation of ISOW — a precursor water mass of NADW (Mauritzen, 1996) — makes it an integral component of the MOC that controls CO_2 partitioning between the atmosphere and deep ocean and, consequently, exerts an important control on global climate.

We used a combination of established surface and deep water ocean proxies to investigate Holocene centennial to millennial scale climatic variability (Figs. 2–4). To examine the deep MOC we employed the sortable silt mean size ($\overline{SS}$) and the carbon isotopic (δ^{13}C) composition of the epifaunal benthic foraminifera *Cibicidoides wuellerstorfi*. All isotopic determinations were performed using a Thermofinnigan MAT 252 mass spectrometer and carbonate preparation device. Isotope values are reported relative to Pee Dee Belemnite using the standard NBS-19. The average analytical precision of the standard analyses over the period of the investigation is better than $\pm$0.03‰ for δ^{18}O and $\pm$0.02‰ for δ^{13}C measurements. In the subpolar North Atlantic the benthic δ^{13}C is generally interpreted as an indicator of changes in the relative proportion of nutrient-depleted North Atlantic Deep Water (NADW; high δ^{13}C) and nutrient-enriched Southern Source Water (SSW; low δ^{13}C) (e.g., Duplessy et al., 1988; Oppo et al., 2003). Grain size distributions of the fine terrigenous fraction were determined using a Coulter Multisizer III with an analytical precision of 1–4% for $\overline{SS}$. The $\overline{SS}$ is a palaeocurrent speed proxy representing the mean grain size of the 10–63 μm terrigenous fraction, where a higher mean reflects stronger near-bottom flow and vice versa (McCave et al., 1995).

Power spectra were calculated using the multi-taper method with seven data-tapers and spectral confidence levels located using the robust AR(1) modelling of median-smoothed spectra. For the confidence levels of the power spectra we allowed for the effect of zero-padding. Prior to analysis data was Gaussian interpolated to a common time interval of 100 years.

3. Results and discussion

The $\overline{SS}$ record indicates the presence of a highly variable ISOW flow throughout the Holocene on centennial to millennial time scales (Fig. 2b). The higher temporal resolution of NEAP4K allows the detection of extensive centennial scale variability superimposed on the millennial scale flow speed oscillations recorded in NEAP15K (Fig. 2a, Bianchi and McCave, 1999) from the deeper Gardar Drift at 2847 m. The changes in ISOW flow speed recorded in NEAP4K do not clearly match the Holocene pattern of the benthic δ^{13}C data and an obvious correlation is only occasionally present, as for example around 2700 yrs B.P. (Fig. 2b and c solid circles). However, a much better relationship is observed when the grain size curve is compared with the benthic

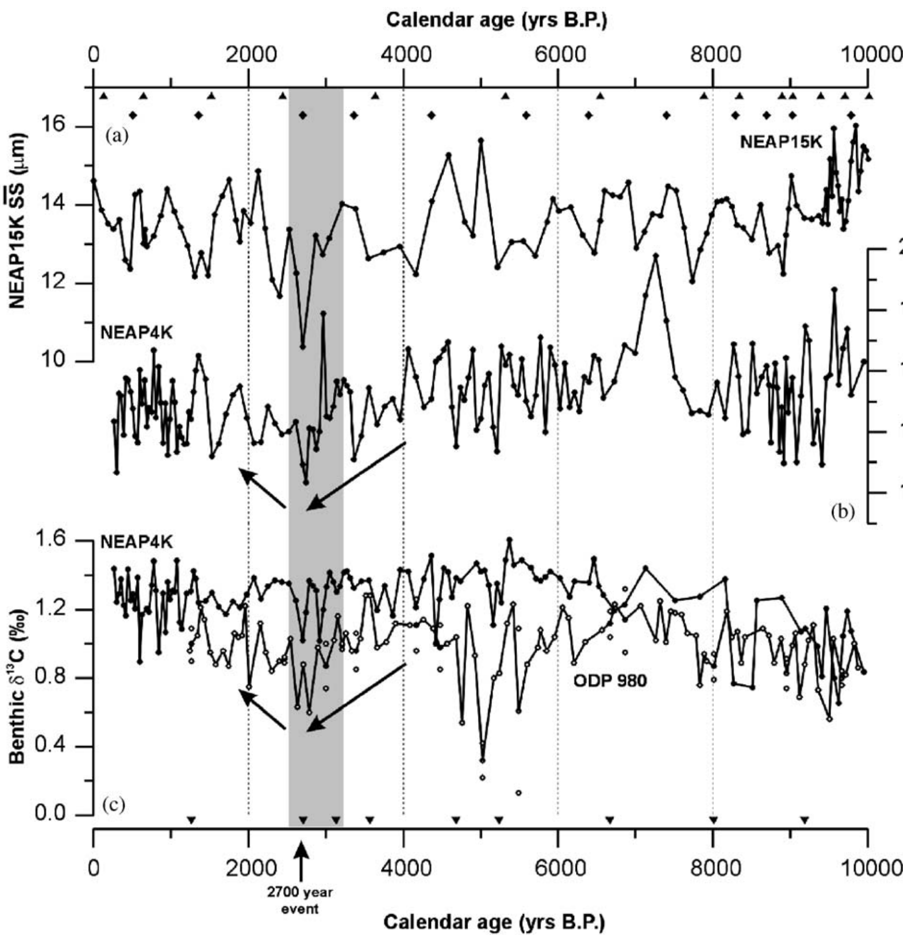

Fig. 2. Summary of NEAP4K palaeocurrent data and other Holocene proxy records of deep ocean circulation for comparison (all plotted to age): (a) NEAP15 K $\overline{SS}$ (Bianchi and McCave, 1999), (b) NEAP4K $\overline{SS}$, (c) benthic $\delta^{13}C$ (*Cib. wuellerstorfi*) from NEAP4K (solid circles) and ODP Site 980 (Oppo et al., 2003) (open circles). Up triangles, diamonds and down triangles are dated levels in sediment cores NEAP15K, NEAP4K and Site 980, respectively. Shading shows the 2700-year event.

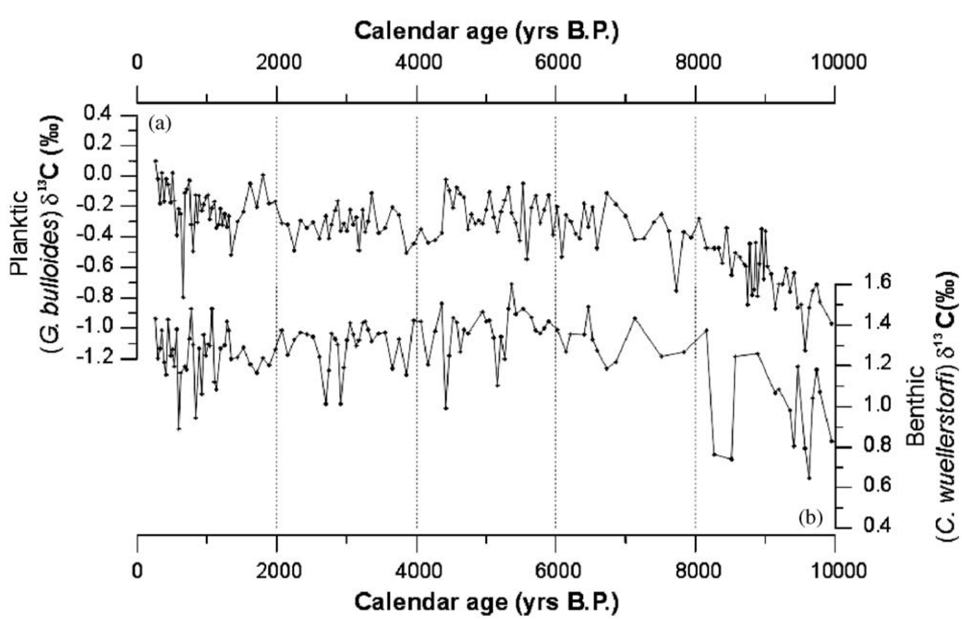

Fig. 3. Comparison of the planktic and benthic $\delta^{13}C$ data from NEAP4K: (a) planktic $\delta^{13}C$ measured on *G. bulloides*, (b) benthic $\delta^{13}C$ measured on *Cib. wuellerstorfi*.

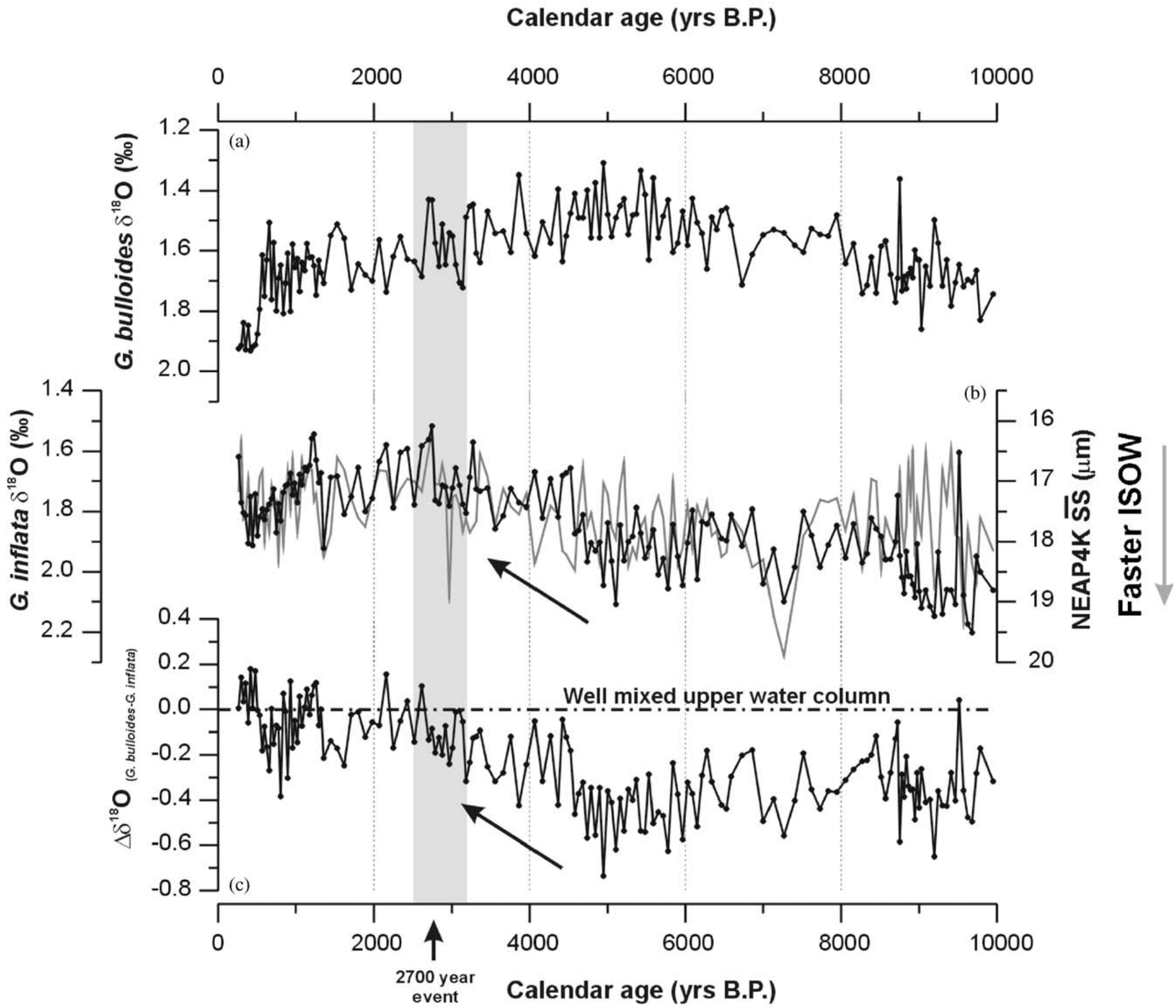

Fig. 4. Summary of NEAP4K Holocene surface ocean data (all plotted to age): (a) *G. bulloides* δ^{18}O, (b) *G. inflata* δ^{18}O (black line) overlain onto $\overline{SS}$ (grey; note reverse scale) and (c) $\Delta\delta^{18}O_{G.bulloides-G.inflata}$. $\Delta\delta^{18}O_{G.bulloides-G.inflata}$ zero line signifies a well mixed upper water column. Arrow highlights increasing upper water column mixing and decreasing NAC influence at the NEAP4K site.

δ^{13}C at Site 980 in the Rockall Trough (Oppo et al., 2003; 2179 m water depth) (Fig. 2b and c open circles). This greater correspondence may be accounted for by the position of NEAP4K which lies some 850 km to the northwest and ~500 m shallower than Site 980, making it more isolated from the geochemical changes affecting Site 980 that presently lies under the influence of deep waters that are partly of southern origin (Oppo et al., 2003) as confirmed by the predominant 0.3‰ offset between the geochemical records at the two sites shown in Fig. 2c. Nonetheless, the abrupt, 0.3–0.4‰ decreases seen in the benthic δ^{13}C over Björn Drift may provide evidence of the severity of some of the SSW incursions into the subpolar North Atlantic during periods of slackened ISOW production of the Holocene. Fig. 3 shows a comparison of the planktic and benthic δ^{13}C records from NEAP4K. It indicates a strong millennial scale relationship between surface and deep ocean chemistry. This suggests some of the change in the NEAP4K benthic δ^{13}C record can be ascribed to variability in the preformed signature of the water. The amplitude and high frequency variability of planktic and benthic δ^{13}C records suggest that such an influence is also occasionally present during shorter-lived events (e.g. ~10,000 to 9000 yrs B.P. and after ~1000 years B.P.). This is supported by Chapman and Shackleton (2000), who demonstrated a link between surface ocean δ^{13}C and ISOW activity from measurements undertaken on core NEAP15K from the southern Gardar Drift (Fig. 1). Moreover, the lack of a clear response in either of the benthic δ^{13}C records in Fig. 2c during the ISOW flow speed maximum at ~7200 years B.P. may imply an upper limit to the sensitivity of the δ^{13}C composition of the bottom waters.

The difference in the foraminiferal δ^{18}O composition of the surface dwelling *G. bulloides* and the thermocline species *Globorotalia inflata* ($\Delta\delta^{18}O_{G.\ bulloides-G.\ inflata}$) has been calculated to estimate the degree of upper ocean stratification (Fig. 4c). A study of surface sediments from the northeast Atlantic suggests $\Delta\delta^{18}O_{G.\ bulloides-G.\ inflata}$ values of around zero indicate cooler, well mixed surface waters to the northwest of the Subarctic Front (SAF), where deep wintertime mixing to at least 200 m depth extends into late spring/early summer (Ganssen and Kroon, 2000). Greater upper ocean stratification is associated with the NAC that flows approximately over the Rockall Plateau and to the southeast of Björn Drift. Therefore, we interpret lower $\Delta\delta^{18}O_{G.bulloides-G.inflata}$ values as a signal of the northwest penetration of the NAC and the associated retreat of the SAF towards and beyond the NEAP4K core site. Increasing sea surface temperatures (SST) and stratification over the Björn Drift during the early Holocene reflect a gradual zonal shift of the SAF which resulted in a prolonged period of strong, but still variable, NAC influence (minimum $\Delta\delta^{18}O_{G.\ bulloides-G.\ inflata}$) between ~8000 and 4800 years B.P. that coincides with the Holocene thermal maximum (Fig. 4c). This observation is consistent with lightest Holocene δ^{18}O values for *G. bulloides* (Fig. 4a) and maximum Holocene sea surface salinities and SSTs throughout the high latitude North Atlantic (Kerwin et al., 1999), with SSTs 2–3°C warmer than present over the Rockall Plateau (Duplessy et al., 1992). Between ~4500 and 2100 years B.P. a trend towards increasingly well mixed upper water column implies decreasing NAC influence and southeastwardly migration of the SAF. This is supported by the decreasing abundance of *G. inflata* in NEAP4K, which in the North Atlantic occurs in highest quantities in the warmer Gulf Stream waters (Kipp, 1976), and changes in the nannofossil assemblage structure over Gardar Drift (Giraudeau et al., 2000).

The variability in $\Delta\delta^{18}O_{G.\ bulloides-G.\ inflata}$ is predominantly driven by fluctuations in the δ^{18}O composition of the deeper dwelling *G. inflata* (Fig. 4b and c). After ~8000 years B.P., a persistent millennial to centennial scale surface climate-deep water linkage is clearly demonstrated by the closely related changes in the ISOW flow speed and the *G. inflata* δ^{18}O (Fig. 4b; note the period of extreme values recorded by both proxies around 7200 years B.P.). A strengthening in the relationship from the early to late Holocene suggests a possible increasing sensitivity of ISOW production in the Nordic Seas to surface forcing from lower latitude waters transported by the NAC. A link between surface ocean conditions in sub-polar North Atlantic, rates of deep water production in the Nordic Seas and climate in the same region is suggested by a record of July atmospheric air temperatures based on palynological reconstructions over the past 10,000 years B.P. from a tree-line locality in northwestern Finland (Fig. 5b; Seppä and Birks, 2002). The comparison of the atmospheric temperature data with the $\overline{SS}$ record of NEAP4K (Fig. 5) highlights a strong similarity for the best part of the Holocene in the longer-term trends as well as in some of the key sub-millennial features of the

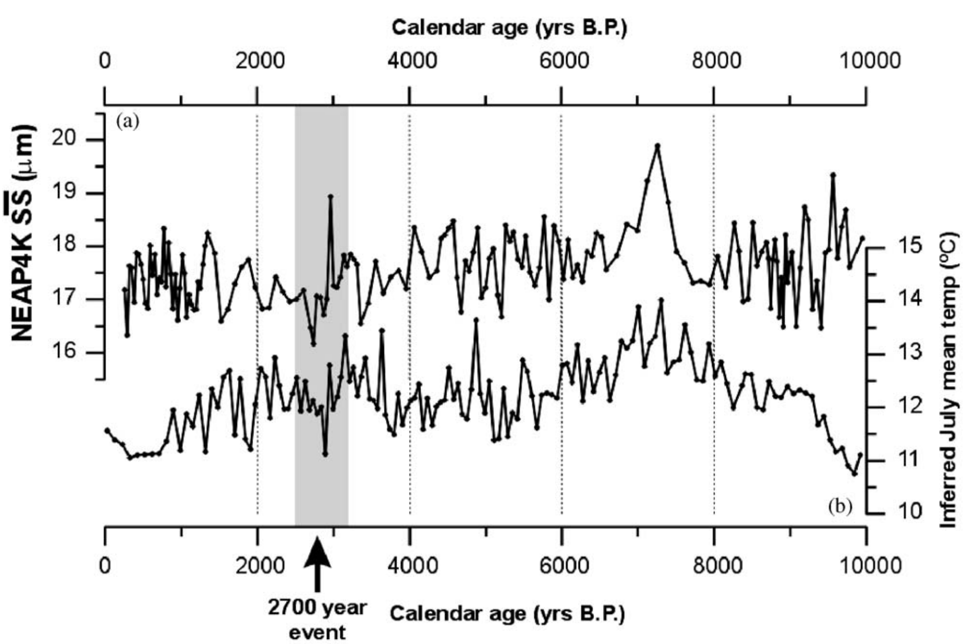

Fig. 5. A comparison of (a) the NEAP4K $\overline{SS}$ proxy record for relative ISOW flow speeds and, (b), pollen-based July mean temperature reconstruction from lake Toskaljavri in the arctic-alpine region of northern Finland (Seppä and Birks, 2002).

proxy curve. Notably, the interval of peak ISOW flow speeds centred at ~7200 years B.P. coincides with maximum Holocene atmospheric temperatures in the pollen record. While, within dating errors, the centennial-scale minimum in ISOW flow speeds at ~2700 years B.P. is coincident with the coolest mid-late Holocene Fennoscandian temperatures. These observations support the reliability of the $\overline{SS}$ data as a sensitive proxy for ISOW flow intensity fluctuations.

A recently discovered correlation between production rates of cosmogenic nuclides (^{14}C and ^{10}Be) and drift ice deposition recorded in North Atlantic sediments led to the suggestion that a significant part of the centennial to millennial scale climate variability during the Holocene was driven by solar forcing, with changes in NADW production as a possible amplifying mechanism that could contribute to their global imprint (Bond et al., 2001). The NEAP15K palaeocurrent record suggests that changes in the speed of the ISOW flow varied with a ~1500-year periodicity (Bianchi and McCave, 1999), apparently in accordance with the North Atlantic drift ice cycle. However, times of reduced ISOW speed do not coincide with the peak IRD deposition and close scrutiny of the spectral evidence from NEAP15K revealed a broad band of quasiperiodic variability rather than a narrow defined periodicity (Wunsch, 2000). The $\overline{SS}$ record from NEAP4K shows significant (>95% confidence level) concentration of variance at 1000 year and 400 year although the millennial scale cyclicity is poorly defined and represents a quasiperiodic variability with additional weaker (>90%) 1400-year and 700-year cycles. These data are in agreement with evidence of more prominent 900–1000 year and 400–550 year periodicities in Holocene climate proxies (Stuiver and Braziunas, 1989; Chapman and Shackleton, 2000; Schulz and Paul, 2002; Risebrobakken et al., 2003).

A comparison of the NEAP4K $\overline{SS}$ record with the Holocene ocean stack of drift ice deposition (Bond et al., 2001; Fig. 6) shows some similarity, with periods of elevated drift ice deposition generally corresponding to higher inferred ISOW flow intensity. The most notable examples occur at ~7200; 5300; 4600; 4100; 3000 and 2700–1400 years B.P., when the peaks (or trends) in flow speed correspond, within dating errors, to drift ice deposition events. This type of correlation poses important questions regarding the interpretation of these sedimentological data, as the common contention has been that an increase in drift ice deposition should correspond to a reduction in the convective activity of the Nordic Seas (Bond et al., 2001) and, thus, a decrease in the $\overline{SS}$ rather than the often observed increase. Both our surface ocean climate records (Fig. 4b and c) and, within dating error, the temperature fluctuations recorded in north-western Finland (Fig. 5b) support the interpretation of the observed $\overline{SS}$ variability in NEAP4K as an indicator of changing ISOW flow speed.

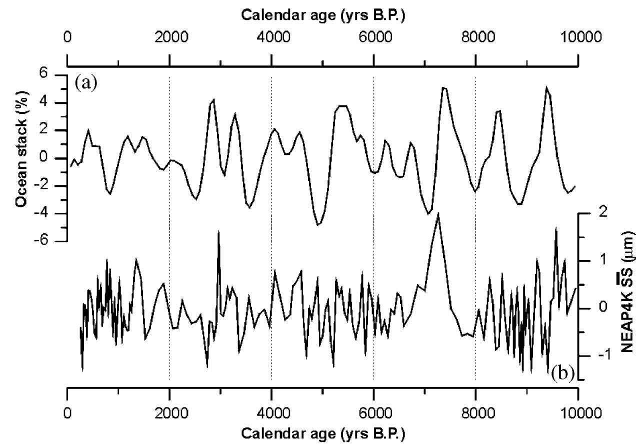

Fig. 6. A comparison of (a) stacked record of petrologic tracer abundance of drift ice (Bond et al., 2001) and, (b), relative ISOW flow speeds plotted to age. The NEAP4K $\overline{SS}$ record has been detrended using a polynomial line fit.

There is a clear need to determine both sedimentological proxies from the same samples where other independent evidence is also available to document the activity of the overturning circulation of the North Atlantic (e.g. Cd/Ca).

The 8200-year event is generally regarded as the most significant Holocene cooling episode, with a clear expression in the Greenland ice core (Alley et al., 1997), in sediments from the Norwegian Sea (Risebrobakken et al., 2003), and effects felt widely in the North Atlantic region (e.g. Baldini et al., 2002). The NEAP4K benthic $\delta^{13}C$ data indicate the presence of an ~400 year long negative excursion beginning at 8570±140 years B.P. (Fig. 2c) that is partly supported by a brief decrease in ISOW flow speed centred at ~8400 years ago (Fig. 2b). However, the absence of a similar shift in the benthic $\delta^{13}C$ at Site 980 (Fig. 2c) is enigmatic. Also, considering the apparent severity of the 8200-year event, the $\overline{SS}$ signal appears to be rather muted, especially when compared to other significant changes in ISOW flow speeds. Therefore, at best, the nature of the deep ocean circulation in the North Atlantic during the 8200-year event remains indistinct. Nonetheless, it also appears unlikely that the 8200-year event caused a prolonged and dramatic perturbation in the MOC of the North Atlantic.

We find that the most pronounced and consistent deep water perturbation present in all the proxy records of Fig. 2 takes place ~2700 years ago, when the transition, starting at ~4500 years B.P., from strongly stratified to well mixed surface ocean water at the NEAP4K site ends (Fig. 4c). Each of the deep circulation proxies displays an abrupt decrease in the contribution of ISOW/NADW associated with this event and the minimum flow speed for the Holocene is reached in both the NEAP4K and NEAP15K sedimentological records. Indeed, a $\overline{SS}$ value of ~10.5 μm in NEAP15K implies the virtual absence of ISOW flow suggesting significant shoaling/weakening of the overflow waters. Similar, recent evidence suggests that a change in the nature of Arctic Intermediate Water (AIW), a major contributor to the formation of ISOW (Mauritzen, 1996), over the Vøring Plateau (Norwegian Sea) (Risebrobakken et al., 2003), corresponds to the 2700 year B.P. minimum ISOW flow speeds. This is supported by the coincidence of the south-east migration of the SAF over the site of NEAP4K in the late mid-Holocene (Fig. 4c) with the retreat of the Arctic front from the eastern Norwegian Sea (Risebrobakken et al., 2003). Risebrobakken et al. (2003), suggest their data might be indicative of prolonged intervals of the North Atlantic Oscillation (NAO) in either its positive or negative mode. If there was a shift in the nature of the AIW supply to the Norwegian Sea that started at ~4000 years B.P. as a response to weakening westerlies and reduced insolation forcing (Risebrobakken et al., 2003), it is likely that this water mass played an important part in the fluctuating production rate of ISOW. However, the changing nature of the surface NAC supplied to the Nordic Seas described here must also have had a competing role, as demonstrated by the close correlation between the *G. inflata* $\delta^{18}O$ and $\overline{SS}$ records. We suggest that the oceanic changes associated with the 2700-year event appear to be part of at least a regional and possibly global signal occurring at this climatic transition that includes a step rise in the atmospheric $\Delta^{14}C$ concentration, an equatorward relocation of the mid-latitude storm tracks and glacier advances in South America and northwestern Europe (van Geel et al., 1999, 2000).

4. Conclusions

We have shown significant new evidence that demonstrates the presence of substantial Holocene variability of one of the most important components of the Atlantic MOC. However, differences exist when the variability of the deep outflows from the Nordic Seas during the Holocene is reconstructed using the $\overline{SS}$ grain size proxy for current flow vigour and benthic $\delta^{13}C$ data for varying nutrient concentration of the bottom waters. Some of the short term $\delta^{13}C$ excursions reported here and elsewhere clearly reflect real shifts in the water mass structure of the deep Northeast Atlantic, but a comparison of the planktic and benthic $\delta^{13}C$ records over the past 10,000 years suggests the latter also contain a preformed component. Some peak ISOW flow speeds recorded by the $\overline{SS}$ grain size proxy coincide with maximum drift ice deposition suggested by Bond et al. (2001). This poses some important questions regarding the interpretation of both proxies. The surface ocean evidence from the northern Iceland Basin and atmospheric temperature data from northwestern Finland strongly support the $\overline{SS}$ data as a proxy for ISOW flow fluctuations.

Finally, as it has been shown that the recent decrease in ISOW production since around 1960 may be compensated by a shift to stronger formation of intermediate waters (Hansen et al., 2001; Dickson et al., 2002), we are presently unable to assess the integrated behaviour of the Atlantic MOC during the Holocene. Certainly, the possibility that our long-term decreases (increases) in ISOW flow are not compensated by either increased (decreased) Denmark Strait overflow or increased (decreased) convection in the Labrador Sea cannot be excluded. No matter what, the correspondence of long- and short-term trends in our Holocene records demonstrates a direct linkage between surface processes in the subpolar northeastern Atlantic and deep circulation changes from the Iceland-Scotland overflow component of the MOC. This implies that surface and deep-ocean fluctuations during most of the Holocene appear to be essentially synchronous. These results underscore the critical need to understand the forcing of ocean circulation changes in the absence of large ice sheets.

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