Timing and mechanisms of surface and intermediate water circulation changes in the Nordic Seas over the last 10,000 cal years: a view from the North Iceland shelf

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Abstract

The North Iceland shelf bears essential components of the present surface and intermediate circulation of the northern North Atlantic. Instrumental and historical data give evidence of the sensitivity of this domain to broad, regional-scale oceanic and atmospheric anomalies. Our investigation of the paleohydrological variability of the North Iceland throughout the last 10,000 cal yr suggests that atmospheric forcing alone, through combined changes in strength of the wind stress curl and sea-level atmospheric pressure pattern over the Nordic Seas, is sufficient to explain the recorded changes in origins and dynamics of surface and intermediate water masses. Our biotic proxies, coccoliths and benthic foraminifera, were extracted from a giant piston core (MD99-2269) collected in a shelf trough where sediment accumulated at an excess rate of 2 m/kyr. The mid-Holocene from 6.5 to 3.5 cal kyr BP was a time of peaked carbonate production and subsequent sedimentation, and strong water-column stratification with a thick layer of cold-fresh Arctic surface water overlapping an enhanced flow of Irminger/Atlantic Intermediate water. Applying conditions triggering present-time carbonate plankton blooms in the studied area, we infer that a lowered cyclonic activity associated with decreased winter storms and reduced production of Arctic Intermediate Water in the Iceland Sea were conductive of the recorded mid-Holocene water column structure. The opposite situation (warm Atlantic surface water, low vertically-integrated inflow of Irminger water, abutment of Arctic Intermediate water in deep shelf troughs) characterized the early Holocene as well as a shorter late Holocene period centred at 2 cal kyr BP. The Little Ice Age (ca. 0.2–0.6 cal kyr BP) and a short event at around 3 cal kyr BP stand as times of extreme advection of polar waters and extended sea–ice development. A comparison of the recorded long-term Holocene evolution of water column structure off Northern Iceland with climate and hydrological changes in the northeastern Atlantic suggests that the strength of Atlantic inflow into the Nordic Seas was subjected to a balance between the Irminger and the Norwegian branches. This balance is thought to be mostly related to changes in the intensity and location of westerly winds and associated atmospheric pressure gradients in the North Atlantic.

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1. Introduction

The North Iceland shelf has recently been the subject of intensive marine geological investigations which showed that this restricted area encapsulated, throughout the last deglaciation and Holocene periods, oceanographic and atmospheric variability that occurred over a much broader area (Andrews et al., 2000; Jennings et al., 2002; Andrews and Giraudeau, 2003; Andersen et al., 2004). Historical, as well as instrumental records have highlighted the sensitivity of this domain to recent oceanic and atmospheric anomalies such as the Great Salinity Anomaly (GSA) in the late 1960s, or the Little Ice Age (LIA) cold spell dated off northern Iceland at 750–100 cal yr BP (Knudsen and Eiriksson, 2002). Both events shared common features off northern Iceland including surface water cooling and freshening associated with increased influence of arctic and polar waters.
Those surface water changes have a profound effect on both primary productivity and sea-ice extent as evidenced by hydrographic survey conducted in these waters over the last 50 yr (Thordardottir, 1984). In addition, it has been shown that surface water changes on the North Iceland shelf are tightly associated with altered overturning of deep and intermediate waters in the Iceland and Greenland seas (Malmberg and Jonsson, 1997), as well as with variations in the flux of Atlantic waters entering the Norwegian Sea (Blindheim et al., 2000). Atmospheric forcing, through variability in strength of the wind stress curl over the Nordic Seas (Jonsson, 1992), as well as changes in the state of the atmospheric pressure system over the North Atlantic (Dawson et al., 2003; Blindheim et al., 2000), are seen as the main drivers of changes in the water-mass structure of the northern North Atlantic.

The North Iceland shelf bears essential components of the present surface and deep circulation of the northern North Atlantic (Fig. 1; Hopkins, 1991; Stefansson, 1962). It is located close to the Arctic Front which separates Arctic/Polar water masses carried by the south-eastward flowing East Iceland Current (EIC) from the North Iceland Irminger Current (NIIC), a branch of the Irminger Current which rounds the western side of Iceland and feeds the North Iceland shelf with warm Atlantic waters. The NIIC reaches the inner part of the North Iceland shelf while the deeper realms are occupied by Arctic Intermediate waters (AIW), down to approximately 500 m, which is formed by convection in the Iceland and Greenland seas (Rytter et al., 2002; Malmberg and Jonsson, 1997). Starting from the mid-shelf area, Atlantic Water carried in the NIIC is submerged beneath colder, fresher Arctic Water carried by the EIC (Fig. 1). This water-column stratification is well displayed in Hunafloaall, where the wedge of Atlantic Water between 100 and 350-400 m water depth is cooled to 3.5 °C and freshened to 34.9%. This submerged vestige of the NIIC is termed Irminger Intermediate Water (IIW). Beneath the IIW, temperatures decline with depth from 3.5 °C to slightly lower than 0 °C in the deepest parts of the northern shelf troughs. Salinities are 34.8%, less than those in the IIW. The bottom water mass represents upper Arctic Intermediate Water (Swift, 1986), although the deepest parts of the northern troughs may contain Norwegian Sea Deep Water (Rytter et al., 2002).

We investigate the water-column dynamics off NW Iceland throughout the last 10 000 cal yr using the combined records of coccoliths, proxies for surface water conditions, and benthic foraminifera as tracer of intermediate and bottom water masses in the nearby Nordic Seas. Our higher time resolution proxy in the present study, coccoliths, has been successfully tested in recent works dealing with the Holocene short and long-term evolution of the North Atlantic Drift south of Iceland (Giraudeau et al., 2000), and of its NIIC branch.

![Fig. 1. (A) Surface circulation around Iceland (A), with location (star) of the Iceland Sea sediment trap discussed in the text. (B) Location of the studied core. (C) Water masses across the NW Iceland shelf as depicted from the water column distribution of potential temperature in the vicinity of the core location (after Andrews et al., 2003b).](image)
over the inner North Iceland shelf (Andrews and Giraudeau, 2003). It complements another surface water proxy, diatoms, which have been recently investigated in MD99-2269 (Andersen et al., 2004). Recent works on the modern and fossil distribution of benthic foraminifera around Iceland highlighted the close correspondence of species distribution with bottom water-masses and their characteristics (Ryutter et al., 2002; Jennings et al., 2002; Jennings et al., 2004).

2. Material, core chronology and methods

Giant piston core MD99-2269 (66° 37’N–20° 51’W) was collected as part of the IMAGES V cruise of RV Marion Dufresne. The core was retrieved at 365 m water depth from a 30 m thick sediment unit on the floor of Hunafloaall, a north–south orientated depression off N/NW Iceland. Previous works have shown that this core contains a continuous Holocene sedimentary series which accumulated at a rate close to 2 m/kyr (Andrews et al., 2003a). The construction of the shelf sediment unit and the recorded excess rate of sedimentation are mainly explained by the combination of bottom currents focussing and an ample continuous supply of volcanic material from the nearby submarine Kolbeinsy Ridge, a fraction which exceeds both the detrital and biogenic components over the North Iceland shelf (Oehmig and Wallrabe-Adams, 1993).

The stratigraphic framework has recently been revised by Andrews et al. (2003b). It is essentially based on 11 AMS14C dates measured on molluscs, which were ultimately converted to sidereal years with the CALIB 4.3 program (Stuiver et al., 1998) in applying a constant 400 yr reservoir age (ΔR = 0). Additional age control was provided by the occurrence of the Saksunarvatn tephra (10.18 cal ka; Grönvold et al., 1995) toward the base of the core. These 12 dates (Fig. 2) define an age/depth model given by the linear equation: age (cal yrs BP) = −15.8 + 4.9 × depth (cm) (R² = 0.997). This best-fit equation suggests that sediment accumulated at the core location at the constant rate of ~2 m/ky (Andrews et al., 2002). The hypothesis of a constant reservoir age for the North Iceland shelf throughout the last 10,000 yr has recently been challenged by Eiriksson et al. (2000) and Knudsen and Eiriksson (2002) who, on the ground of coupled AMS14C and tephra-based chronologies, suggested a 150 yr increase in reservoir age between 3 and ca. 1 cal kyr BP from a shelf-trough farther east on the shelf. However, ongoing research using tephra horizons (Hekla tephra) on core MD99-2269 did not result in significant changes in reservoir age at the core location, probably because Hunafloaall is closer to the influence of Atlantic/Irminger waters than are the more arctic-influenced sedimentary archives studied by Eiriksson and collaborators (Kristjansdottir, 2002). Additional radiocarbon dates combined with the identification of tephras will undoubtedly lead to modifications in the details of the chronology. Indeed, although a linear sedimentation rate has been used in this and previous papers (Andrews et al., 2003a), new but unpublished AMS14C dates suggest departures from this model, especially for the period > 8 cal ka.

Sample preparation for the study of coccoliths and benthic foraminifera involved standard techniques summarized in Andrews and Giraudeau (2003) and Jennings et al. (2002), respectively. Coccolith observations and census counts were conducted using a light microscope at 1250 × magnification, following a series of dilution and filtration treatments of a pre-weighed amount of dry bulk sediment as described by Andruleit (1996). Census counts were expressed as coccolith concentrations (specimens/g of dry bulk sediment), and subsequently transformed into accumulation rates (specimens/cm²/time) using the estimated mass accumulation rate (Andrews et al., 2003b). A calculation of coccolith carbonate contribution to the bulk sediment was done following the method described by Beaufort and Heussner (1999) and data set given in Young and Ziveri (2000), which is based on estimates of the mean carbonate mass of the various species found in core M99-2269. Sample resolution for the coccolith analyses varied from 5 cm for samples representative of the last 3000 yr and of the 7.5–8.5 kyr BP interval, to 10 cm for the rest of the core. This translates into a 20–50 yr time resolution.

Samples for foraminiferal analysis were taken at 50 cm spacing (about 250 yr) throughout the length of the core. The samples were wet-sieved at 63 and 106 µm. The > 106 µm fractions were divided with a microsplitter until the split contained between 200 and 300 benthic foraminifers. Foraminifera in the entire split were identified to genus and species levels and tallied into percentages.

Data on total carbonate content, measured at 5 cm interval using a Coulometer in the Sedimentology Laboratory at INSTAAR (Boulder, CO), were taken from Andrews et al. (2003b).

3. Results

3.1. Coccolith species distribution and coccolith carbonate

Coccolith species diversity is typically low as expected for this arctic/subarctic setting (Baumann et al., 2000; Andrews and Giraudeau, 2003). Dominance is equally shared between Coccolithus pelagicus, the cold-end member of the coccolithophore community in North Atlantic waters, and the ubiquitous Emiliania huxleyi (Fig. 2) which is presently responsible for extensive
blooms in transitional/subarctic waters as well as in shallow settings along Norway and NE America (Brown and Yoder, 1994). The subordinate species *Gephyrocapsa mullerae, Calcidiscus leptoporus* and *Syracosphaera* sp., together account for an average 7.5% of the total assemblage throughout the studied interval (Fig. 2). They were grouped as “Irminger water (IW) species” considering their present biogeography (Samtleben et al., 1995) and following the conclusion of Andrews and Giraudieu (2003) that this species group can be used off northern Iceland as a tracer of surface Irminger/Atlantic water inflow.

Total coccolith concentrations follow a simple bell-shape trend with low values in the early Holocene, a regular increase toward maximum concentrations centred at 4-4.5 cal kyr BP., and a subsequent decrease with rapid high amplitude changes toward the late Holocene (Fig. 2). The range of bulk coccolith sedimentation (mean = 7.4 × 10⁸ specimens/g) falls within Holocene values given for the Iceland Sea (Andruleit and Baumann, 1998) but is nearly double the Holocene values of bulk coccolith carbonate sedimentation estimated at a nearby shallower setting due south of the studied core (Andrews and Giraudieu, 2003). This
difference suggests that the deeper, offshore setting of core MD99-2269 may be more favourable to coccolithophore production and subsequent sedimentation than nearshore, shallow environments off northern Iceland. Our estimates of bulk coccolith accumulation rates (Fig. 2; mean = $120 \times 10^6$ specimens/cm$^2$/yr) are on average 10 times higher than values given for surface sediments of the Nordic Seas (Andruleit, 2000), an indication of the degree of sediment focusing responsible for the construction of the shelf sediment body where the studied core was retrieved.

The linear sedimentation model implies that sediment focusing did not disturb the information on surface water changes given by the coccolith concentration, i.e. that there was no apparent changes in both the degree of focusing, and the amount of dilution by non-coccolith (mainly terrigenous) components throughout the last 10 000 yr. The record of bulk carbonate content at the core site supports this idea, as Andrews et al. (2003b) showed that the carbonate record of MD99-2269 has a true regional significance, being similar, both in trend and absolute values to nearby core sites barely affected by strong sediment focusing. We will therefore argue in the following section that the record of coccolith concentration is a reliable tracer of surface water dynamics.

The record of total carbonate weight % indicates that net carbonate accumulation peaked between ca. 3.5 and 6.5 cal kyr BP (Fig. 3). Our independently calculated values of coccolith carbonate content indicate that changes in total carbonate content can be attributed largely to changes in this biogenic fraction which contributes on average to more than 50% of the total CaCO$_3$ wt%. Large peaks in the numbers of foraminifera per gram of bulk sediment (not shown) also occur in this interval, supporting carbonate peaks at 6 and 4.2 cal kyr BP. The overwhelming contributor to the coccolith carbonate mass weight is *C. pelagicus*, whose large, highly calcified coccoliths account for more than 95% of the total coccolith mass fraction throughout the last 8 cal kyr BP. In particular, sedimentation of *C. pelagicus*, alone, explains between 70% and 90% of the peaks in bulk carbonate accumulation at 6 and 3.8 cal kyr BP (Fig. 3). The hydrological conditions which lead to the mid-Holocene (3.5–6.5 cal kyr BP) high carbonate content over the North Icelandic shelf sediments must therefore be discussed in view of the physical and chemical status of the photic layer which promotes an enhanced primary production of *C. pelagicus*.

The downcore record of IW species (Fig. 4) defines two distinct periods of enhanced advection of warm surface Irminger waters off northern Iceland, as proposed earlier by Andrews and Giraudeau (2003). The high resolution stratigraphic framework of core MD99-2269 helps to refine the timing of these decoupled

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**Fig. 3.** Relative contribution of carbonates (bulk and coccolith fractions) to the bulk sediment in core MD99-2269. Both records have been smoothed (3 pt running average). Inset: contribution of *Coccolithus pelagicus* to the coccolith carbonate fraction.
events—the early Holocene interval ending abruptly at 7.2 cal kyr BP, and the more recent period of peak advection of Irminger waters occurring between 2.6 and 0.8 cal kyr BP, an interval including both the European Roman and Medieval Warm Periods (Briffa et al., 1990). Minimum concentrations of IW species in the studied core are centred at 3–3.5 kyr BP. on one hand, and 0.2–0.6 kyr BP. (i.e. Little Ice Age) on the other hand. The mid-Holocene interval of enhanced bulk carbonate and associated peak sedimentation of *C. pelagicus* is characterized by medium to low concentrations of IW species.

3.2. Bottom water conditions: the benthic foraminiferal record

Previous studies on modern benthic foraminifera off northern Iceland and East Greenland (Jennings and Helgadottir, 1994; Rytter et al., 2002; Jennings et al., 2004) show that modern foraminiferal assemblage compositions and foraminiferal concentrations are related to both hydrographical (salinity, temperature and water depths) and biological (food availability) factors, and that these parameters are well resolved in terms of the progression of bottom water-masses from the coastal and inner trough areas influenced by Atlantic waters carried in the Irminger Current to the hydrographically stratified areas farther offshore in deeper areas such as the shelf troughs.

The benthic foraminiferal record in the last 10 000 cal yr of MD99-2269 is dominated by two inversely varying arctic species, *C. neoteretis* and *Cassidulina reniforme*, whose abundances together average 60% (Fig. 5). *Cassidulina reniforme* shows very high relative abundances during the early Holocene (from ca.10 to 8 cal kyr BP.). After 9 cal kyr BP its abundances steadily decline to a minimum between 4.5 and 3 cal kyr BP. After 3 cal kyr BP its abundances begin to rise again, but never to such high values as in the early Holocene (Fig. 5). In no modern Iceland shelf samples does *C. reniforme* occur in such high abundances as it does in the early Holocene interval of MD99-2269 (Jennings et al., 2004; Rytter et al., 2002). Both *C. reniforme* intervals are also characterized by subsidiary contributions of other arctic species including *Nonionellina labradorica* and *Elphidium excavatum* forma *clavata*. These assemblages are consistent with cold bottom waters with salinities greater than 30% generally in areas of seasonal sea–ice cover (Polyak et al., 2002; Jennings and Helgadottir, 1994).

Countering the decline of *C. reniforme*, *C. neoteretis* rises steadily from moderate values of about 15% at 10 cal kyr BP to values close to 60% between 4.5 and 3.5 cal kyr BP. The interval of maximum contribution of *C. neoteretis* coincides with the peak in bulk carbonate and coccolith carbonate contents during the mid-Holocene, from 6.5 to 3.5 cal kyr BP (Fig. 5). Peaks in bulk foraminifera concentration (not shown) coincide in general with peaks in *C. neoteretis* and bulk carbonate percentages. Subsidiary species co-occurring with *C. neoteretis* during its peak abundance include *Pullenia bulloides* and *M. barleeanus*, both infaunal species reflecting high marine productivity and burial of organic matter (e.g. Corliss, 1985, 1991; Wollenberg and Mackensen, 1998a, 1998b). The cold arctic species that attended *C. reniforme*, are absent or occur in very low percentages. *Cassidulina neoteretis* has been described as characteristic of normal marine water masses with stable salinity and temperature (Seidenkrantz, 1995), as well as

![Image](https://example.com/image.png)

Fig. 4. Coccolith concentrations of Irminger Water (IW) species; the black curve is a smooth record (3pt running average) of original data (open dots).
a tracer of relatively warm bottom waters of Atlantic/ Irminger origins within the East Greenland Current on the Greenland shelf (Jennings and Weiner, 1996) or intermediate Atlantic waters (IIW) off northern Iceland (Eiriksson et al., 2000). Its present distribution over the North Iceland shelf, specifically in hydrographically stratified shelf trough environments where the inflowing NIIC reaches the bottom of the water column, clearly confirms its affinity for modified Atlantic waters (Rytter et al., 2002; Jennings et al., 2004). The natural interpretation for the high percentages of C. neoteretis from at least 6 to 3 kyr would be an increasing influence of IIW on the north Iceland shelf during the mid-Holocene, and associated decreased influence of cold Arctic bottom waters.

4. Discussion and conclusions

The combined coccolith and benthic foraminifera Holocene records are indicative of a clear antagonism in physical–chemical status and sources of water masses between the surface and bottom layers of the water column. In the following discussion, we interpret the
Holocene evolution of water-column structure over the North Iceland shelf as a direct consequence of coupled changes in outflow of Arctic bottom and surface waters from the Nordic Seas and inflow of Atlantic waters around western Iceland.

4.1. Hydrological conditions triggering peak carbonate accumulation in the Iceland Sea

As stated earlier, the very high carbonate sedimentation identified during the ca. 6.5–3.5 cal kyr BP Holocene period is correlated with the peak accumulation of the coccolith species *C. pelagicus*. As reviewed by Baumann et al. (2000), *C. pelagicus* is the cold-end member of the coccolithophore community presently thriving in the Nordic Seas. It is one of the few species able to sustain temperatures close to 0 °C, which explains its overwhelming dominance, albeit with low standing stocks, in the polar community of the East Greenland Current (Samtleben and Schröder, 1992). Further east, toward the Norwegian Sea, as well as south of Iceland, the dominance is progressively shared with *E. huxleyi*, a species which is responsible for the summer development of massive blooms in the subarctic North Atlantic (Brown and Yoder, 1994). Beside its classical temperature constraint and northernmost high latitude distribution, *C. pelagicus* has been identified as an abundant taxon in recently upwelled, nutrient rich waters off Southern Africa (Giraudeau et al., 1993) and Portugal (Cachao and Moita, 2000), as well as in surface sediments below or close to the highly productive Polar Front Zone in the southern ocean (Roth, 1994). This species is therefore considered in paleo-studies as a proxy of both cold and highly productive/nutrient-rich waters.

A time series particle flux experiment conducted in the Iceland Sea since 1986 (Fig. 1; Olafsson et al., 2000; joint Iceland Marine Research Institute and Woods Hole Oceanographic Inst. research program) is shedding light into the hydrological processes which presently result in excess sedimentation of *C. pelagicus* in the Nordic Seas. This sediment trap mooring, located to the north-east of the studied core location, captured in the year 1999 a large flux of biogenic carbonate, 86% of which is being composed of monospecific coccoliths. This excess carbonate flux (up to 10 times higher than the annual mean) was related to a summer bloom of *C. pelagicus* with an areal extent of ca. 30,000 km², i.e. the size of Iceland. According to hydrological data collected in the area for the last 3 decades, conditions which led to this monospecific coccolith bloom are associated with nutrient supply, utilization and depletion, coupled with a recent infiltration of a low salinity surface lens of Arctic water into the Iceland Sea (see Dorinda Ostermann, WHOI Project highlights, www.whoi.edu/science/GG). Beside the classical succession of silicate depletion by siliceous plankton, and bloom progression by non siliceous plankton on the remaining pool of nitrates and phosphates, the presence of a 100 m thick low salinity water inducing deeper mixed layer is thought to be the key element triggering the excess production of *C. pelagicus* at the trap location (Dorinda Ostermann, pers. comm.; Ostermann et al., 2000).

4.2. Implications for the mid-Holocene period of excess carbonate accumulation, and for the long-term Holocene evolution of surface and bottom hydrology

We apply these present-time observations to the mid-Holocene period of excess carbonate accumulation at the core location to imply that this 3.5–6.5 cal kyr interval was characterized by the increased influence of cool, low salinity arctic/polar surface waters. The low contribution of Irminger water species to the coccolith assemblage during this time interval (Fig. 4) indeed suggests that surface waters over the North Iceland shelf were not of Atlantic origin. Such excess carbonate production necessitates a nutrient pool which is hardly consistent when considering the sole nutrient-poor, fresh surface layer of arctic origin.

As shown by Thordardottir (1984), on the basis of hydrological data collected over the last 30 yr, Atlantic waters constitute the main source of nutrients to the North of Iceland. The benthic foraminiferal record from core MD99-2269 suggests that bottom waters over the north Iceland shelf carried a clear Atlantic/Irminger signature during the mid-Holocene period of peak carbonate sedimentation (Fig. 5). We therefore argue that (1) a deepened mixed layer induced by the input of cool, fresh arctic surface waters, coupled with an intermediate/bottom water source of nutrient is capable of inducing excess production and subsequent sedimentation of *C. pelagicus* coccolith carbonates; (2) the flow of nutrient-rich Irminger Intermediate waters around NW Iceland was strongly enhanced during this mid-Holocene period to the prejudice of outflow and abstraction of AIW over the North Iceland shelf.

Both assumptions can be reconciled and explained based on recent observations and a conceptual framework of hydrographic and atmospheric variations in the Iceland Sea as reviewed by Malmberg and Jonsson (1997). According to these authors, and following earlier ideas elaborated by Aagaard (1972) and Jonsson (1992), the strength of the wind stress curl over the Iceland Sea is crucial in the mechanisms of intermediate convection in this area. In this, a positive wind stress curl over the Iceland Sea gives rise to an enhanced cyclonic circulation in the gyre and upward Ekman pumping. Such a mechanism pumps salty water into the area and effectively reduces stability of the water column in the gyre making intermediate water production more likely to take place.
In addition, instrumental records (Malmberg and Kristmánssohn, 1992) show that a strengthened wind stress curl, and therefore more efficient convection in the Iceland Sea, is positively correlated to the amount of surface Irminger waters in the area. Finally, on a more regional basis, this enhanced cyclonic activity in the Iceland Sea is associated with increased winter storms in the Nordic Seas (Dawson et al., 2003).

Conversely, the late 1960s severe ice conditions in North Iceland waters were that of low wind stress curl as well as reduced water column mixing and intermediate water production in the Iceland Sea, but very strong convection in the Greenland Sea (Malmberg and Jonsson, 1997). Instrumental data also revealed a southward shift in winter storm activity, as well as reduced advection of Irminger surface waters, and concomitant increased influence of polar/arctic surface waters north of Iceland (Meincke, 2002; Malmberg and Kristmánssohn, 1992). All these conditions were associated with a strengthening and eastward extension of the Greenland High (Dickson et al., 1988).

We use the hydrological/atmospherical conditions conducive to these opposite situations as analogues to explain the recorded long term Holocene evolution of surface and bottom hydrology, as well as changing carbonate production over the North Iceland shelf. The early Holocene up to ca. 7 cal kyr BP as well as a shorter late Holocene period centred at 2 cal kyr BP are seen as times of enhanced atmospheric circulation over the Nordic Seas, enhanced production of AIW in the Iceland Sea, and surface water warming off northern Iceland linked to reduced influence of the arctic/polar water-bearing EIC. Our micropaleontological data additionally suggest that such conditions promote an overall rather limited inflow of Irminger water around NW Iceland, this diminished influence of IIW at the bottom of shelf troughs being filled by AIW. These conditions are thought to be primarily constrained by a positive NAO-type atmospheric pattern of enlarged meridional pressure differences over the North Atlantic.

Conversely, the mid-Holocene (ca. 3.5–6.5 cal kyr BP) interval of enhanced carbonate accumulation is viewed as a time of reduced atmospheric and gyre circulation in the Iceland Sea, both conditions affecting intermediate water production (lowered) and cooling/freshening of the surficial waters (increased) in this area. This surface water cooling refers to the “Neoglacial” cooling starting at ca. 6 cal kyr BP as evidenced in the Denmark Strait and south of Iceland on the ground of Ice Rafted Detritus (Bond et al., 2001; Jennings et al., 2002) and coccolith proxies (Giraudeau et al., 2000). Intermediate waters over the North Iceland shelf during this interval had a strong Atlantic signature, in relation with an enhanced flow of Irminger waters which affected the deeper part of shelf troughs. The peculiar situations at ca. 3 cal kyr BP and 0.2–0.6 cal kyr BP (Little Ice Age) which are identified by our micropaleontological proxies (Figs. 4 and 5) as periods of both strongly reduced Irminger surface water influence and low coccolith carbonate sedimentation, stand as times of extreme advection of polar, ice bearing waters, and extended sea-ice development (additional evidences are given by Knudsen and Eiríksson, 2002; see also Lamb, 1979; Jennings et al., 2002).

The diatom record constructed from MD99-2269 (Andersen et al., 2004) is generally consistent with the coccolith dataset presented herein. Diatom assemblages are indicative of a general surface water thermal optimum off northern Iceland from 10 to 6.5 cal kyr BP, but fluctuating sea-surface conditions with evidences for seasonal sea–ice conditions which is consistent with the early Holocene benthic foraminiferal assemblages containing *N. labradorica* (see previous chapter). Andersen et al. (2004) identified the 6.5–3 cal kyr BP period as the “Holocene Transition Period” with a gradual cooling of surface waters of about 4°C suggesting increased influence of arctic surface waters carried by the EIC. As suggested by our data set, the afore-mentioned authors argued that this surface water temperature changes are mostly driven by changes in the strength and location of the Icelandic Low pressure cell and associated westerly winds.

### 4.3. Extending our findings to the Holocene evolution of the northern North Atlantic

Assessing that the Holocene history of the water mass structure over the North Iceland shelf is primarily driven by atmospheric processes acting at the scale of the northern North Atlantic implies that the long term hydrological evolution of other areas of the Nordic Seas, in particular the eastern margin, might have been affected by the same processes.

In this regard it is important to note that the previously discussed summer AD 1999 episode of peak coccolith carbonate production in the Iceland Sea (Olafsson et al., 2000), was part of a larger pattern of increased carbonate production in other high latitude regional seas. This year of excess production of carbonate plankton in the Iceland Sea, shortly followed the year AD 1996 which saw an anomalous drop of the NAO index, a unique return over the last 40 years to the negative values typical of the late 1960’s. Based on hydrographic transects across 48’N, Meincke (2002) indicated that the northward oceanic heat transport across this latitude dropped by 50% the year immediately following AD 1996, thereby suggesting that atmospheric anomalies of this kind have the potential of inducing global cooling in the Nordic Seas. Following this AD 1997 drop in northward heat transport, the Bering, Norwegian and Barents Seas each experienced major coccolithophore blooms (Ostermann, pers.
comm.) during the summer of AD 1998. The Iceland Sea peak carbonate production event in summer AD 1999 might stand as the ultimate manifestation (not repeated in the Nordic seas in AD 2000 or AD 2001) of a 3-year suite of hydro-biological changes induced by a drastic modification in atmospheric circulation pattern.

Instrumental data and observations of present hydrological/climatological anomalies in the Nordic Seas therefore suggest an in-phase response of the southwestern and northeastern domains to changes in the North Atlantic atmospheric pressure patterns. We hypothesize that this relationship is valid when considering the Holocene long-term evolution of hydrology in the Nordic Seas. The recently published record of Holocene SST’s changes off the Western Barents shelf (Sarnthein et al., 2003) indeed correlates very well with the main phase of surface water temperature changes off Northern Iceland (positive relationship) as well as with the overall inflow of Irminger water round NW Iceland (negative relationship) (Fig. 6). This planktic foraminiferal-based estimation is indicative of a much enhanced West Spitsbergen Current during the early Holocene up to 7.7 cal kyr BP as well as around 2 cal kyr BP, both periods being characterized off Northern Iceland by surface water warming and by limited inflow of intermediate Irminger water (Fig. 6). Additional evidence for the regional-scale correlation of changes in atmospheric pressure pattern comes from the estimates of winter precipitation in Southern Norway over the last 10 cal kyr as summarized by Nesje (2002), which shows two main episodes of dry conditions at ca. 8.2 cal kyr BP as well as within the mid-Holocene between 6 and 4 cal kyr BP. Such dry (and cold) conditions over central southern Norway are thought to reflect reduced

Fig. 6. Synthetic plot showing (bottom) selected coccolith and benthic foraminiferal records in core MD99-2269 as proxies of water column dynamics and carbonate productivity, compared (top) with SSTs estimates over the W Barents shelf (Sarnthein et al., 2003).
westerlies and cyclone activity, i.e. a predominantly "negative NAO index weather mode" (Nesje, 2002).

The close correlation between Atlantic water circulation changes and precipitation changes in the northeastern North Atlantic on the one hand, and the pattern of hydrological changes in the Iceland Sea on the other hand, is a clear manifestation that these far-off areas are reacting to the same changes in regional-scale atmospheric patterns. Data presented in this paper suggest that the strength of Atlantic inflow into the Nordic seas was subjected during the Holocene to a balance between the Irminger and the Norwegian (and West Spitsbergen) branches, and that it is mostly related to patterns of atmospheric circulation, via the intensity and location of westerly winds. Our conclusions slightly differ from Andersen et al. (2004) who, based on diatom assemblages only, argue for a common dynamics of both branches of the Atlantic inflow into the Nordic Seas. This disagreement might come from the summer surface ocean temperature signature of diatom records which is more likely to be explained in the light of the Holocene trend in summer insolation at high northern latitudes, than in view of winter-related atmospheric processes (NAO). We argue that the main reason for the observed discrepancy lays in the use, in the present work, of a coupled surface and benthic proxy record, which suggests that the strength of the vertically integrated Irminger water flow (ca. the top 500 m of water column over the North Iceland shelf) was rather negatively correlated with the temperature signature of the surface layer where coccolithophore and diatom populations thrive, over the last 10 000 cal yr.

Whereas it is tempting to consider that these Holocene ocean circulation changes were induced by a "NAO-like" modulation of wind-regime, it is important to notice that contrary to the Norwegian Sea, instrumental records do not seem to show any connection between the NAO index and the Atlantic inflow off Northern Iceland (Olafsson, 1999). Beside the standard problem of using instrumentally verified, short-terms (multi-year in the case of NAO) events as analogs for much longer and persistent events as detected in the sedimentological records, local atmospheric forcing other than NAO might influence ocean circulation around Iceland.

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