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Deep-water renewal in the Skagerrak during the last 1200 years triggered by the North Atlantic Oscillation: evidence from benthic foraminiferal $\delta^{18}O$

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Abstract: Benthic foraminiferal tests of a sediment core from southwestern Skagerrak (northeastern North Sea, 420 m water depth) were investigated for their ratio of stable oxygen isotopes. During modern times sudden drops in temperature and salinity of Skagerrak deep waters point to advection-induced cascades of colder and denser central North Sea waters entering the Skagerrak. These temperature drops, which are recorded in benthic foraminiferal tests via the stable oxygen isotopic composition, were used to reconstruct deep-water renewal in the Skagerrak. In a second step we will show that, at least during the last 1200 years, Skagerrak deep-water renewal is triggered by the negative phase of the North Atlantic Oscillation (NAO). The NAO exerts a strong influence on the climate of northwestern Europe. It is currently under debate if the long-term variability of the NAO is capable of influencing Northern Hemisphere climate on long timescales. The data presented here cannot reinforce these speculations. Our data show that most of the 'Little Ice Age' was dominated by comparably warm deep-water temperatures. However, we did find extraordinary strong temperature differences between central North Sea waters and North Atlantic water masses during this time interval.

Key words: Benthic foraminifera, NAO, $\delta^{18}O$, deep-water renewal, Holocene, Skagerrak, North Sea.

Introduction

Hurrell *et al.* (2003) describe the North Atlantic Oscillation (NAO) as the most prominent and recurrent pattern of atmospheric variability over middle and high latitudes of the Northern Hemisphere. About one-third of the total variance in sea-level pressure and of the hemispheric interannual temperature variance is explained by this large-scale variability of atmospheric masses (Hurrell, 1996; Hurrell and van Loon, 1997; Dickson *et al.*, 2000).

The NAO index is the mathematical description of the normalized sea-level pressure differences between Icelandic low (usually Stykkisholmur or Akureyri) and the Azores high (usually Ponta del Gada) (eg, Hurrell, 1995; Dickson *et al.*, 1996). Its winter index is often used for correlation as it represents the season of strongest forcing (Hurrell, 1995). During mainly positive NAO index winters the weather over northern Europe is warm and stormy due to strong westerlies bringing comparably high temperatures from over the open ocean. Mainly negative NAO index winters result in weaker westerlies taking a more southerly track over middle and southern Europe to the Mediterranean Sea while Scandinavia and northern Europe are influenced by extremely cold and calm conditions coming from the north (eg, Hurrell, 1995; Koslowski and Glaser, 1999; Deser, 2000; Slonosky *et al.*, 2000; Hurrell *et al.*, 2003; Jones *et al.*, 2003).

The NAO positively correlates with temperature and precipitation over Europe. Strongest temperature correlation generally is found over southern Scandinavia between September and March (eg, Hurrell, 1995; Chen and Hellström, 1999; Jones *et al.*, 2003). The strength of the correlation between NAO index and climate, however, varies with time and region (Hurrell and van Loon, 1997; Chen and Hellström, 1999; Slonosky *et al.*, 2000; Jones *et al.*, 2003). As recent studies prove, the Skagerrak and its surroundings seem to be a NAO

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sensitive area. Koslowski and Glaser (1999) correlate winter ice severity in the western Baltic Sea with the state of the NAO. Strong westerlies (positive NAO) cause weak ice production whereas weak westerlies (negative NAO) allow strong ice formation. Moreover, the NAO is known for influencing the marine ecosystem, as comprehensively reviewed by Drinkwater *et al.* (2003). These authors conclude that 'the impacts of the NAO are generally mediated through local changes in the physical environment, such as winds, ocean temperatures, and circulation patterns', which is also the case in the surroundings of the Skagerrak. Based on changing benthic foraminiferal faunas in the Gullmar Fjord/Swedish west coast, Nordberg *et al.* (2000) and Filipsson and Nordberg (2003) differentiated time intervals of high and low bottom-water oxygenation, which depend on the frequency of bottom-water renewal. They found a negative causal relation between the NAO and the oxygenation state of bottom waters. During positive NAO phases with prevailing westerly winds, upwelling of oxygen-rich bottom water in the Skagerrak is prevented. The upwelling, however, is a prerequisite for the deep water-exchange in the fjord. Hagberg and Tunberg (2000) demonstrated that deep-water renewal in the Skagerrak positively correlates with the NAO during the last 30 years. They found 0- to 2-year lags between NAO index and temperature evolution. We will show that the correlation between Skagerrak deep-water renewal and the NAO has existed at least for the last 50 years and presumably even for the last 1200 years.

Currently, it is speculated that the NAO remained for longer time spans in mainly one phase. These time periods, in which the NAO possibly stayed in predominantly one phase are thought to correlate with historically known climate periods, such as the 'Little Ice Age' (LIA; AD 1350–1900, following Hass, 1996) or the 'Mediaeval Warm Period' (MWP, AD 700–1350, following Hass, 1996). The climax of 'Little Ice Age' winters over northern Europe seems to be characterized by calm and extremely cold conditions, possibly a result of predominantly negative NAO index values (Koslowski and Glaser, 1999; Shindell *et al.*, 2001). The 'Mediaeval Warm Period' winters are suggested to be influenced by predominantly positive NAO index values since they were comparably warm, humid and stormy (Shindell *et al.*, 2001; Cook, 2003). Rimbu *et al.* (2003) suggested 'a continuous weakening of a Northern Hemisphere atmospheric circulation pattern similar to that of the Arctic/North Atlantic Oscillation'. They assumed that Arctic Oscillation/NAO possibly plays a role in generating millennial-scale sea-surface temperature trends, reconstructed via alkenone analysis.

The goals of this study are (1) to demonstrate that $\delta^{18}O$ values of benthic foraminiferal tests can be used to reconstruct Skagerrak deep-water renewal, (2) to present a feasible mechanism to explain the connection between the NAO and deep-water renewal in the Skagerrak, and (3) to investigate whether the NAO influences climate in the Skagerrak region on more than the short-term level. For comparison of $\delta^{18}O$ values and the NAO, we used the updated annual NAO index of Hurrell (1995), which is based on sea-level pressure differences between Stykkisholmur/Iceland and Lisbon/Portugal.

Oceanographic settings

The Skagerrak basin, more than 700 m deep, forms the deepest part of the Norwegian Trench and therefore acts as main depocentre for the North Sea (Figure 1). It has an irregular elongate shape with a steep northern and a more gently dipping southern flank. The Recent sedimentation process started after the retreat of the last glacial maximum glaciers (Stabell and Thiede, 1985). Holocene sediments overlie unconformably an eroded Mesozoic basement (eg, Stabell and Thiede, 1985; von Haugwitz and Wong, 1993).

Major parts of the sediments are injected via the Southern Jutland Current (SJC) originating from various areas of the southern and eastern North Sea (Lepland and Stevens, 1996). Sediments of the second sediment source of the Skagerrak, the northern North Sea, are transported via the Southern Trench Current (STC), which is fed by several branches of the eastern branch of the Norwegian Atlantic Current (NwAC) and northern North Sea waters (eg, Svendsen *et al.*, 1991).

The water masses of SJC and STC entering the Skagerrak in mid-to upper water depth (Rydberg *et al.*, 1996) are united in the Northern Jutland Current (NJC), which represents the southern branch of the cyclonic circulation of the Skagerrak. Continuing to the east, superficial brackish water masses of the Baltic Current (BC) mix forming the Norwegian Coastal Current (NCC). Outflowing water masses follow the morphology of the Norwegian Trench along the Norwegian coastline. Smaller amounts of NCC water masses are recycled in the western part of the Skagerrak. The cyclonic circulation of the Skagerrak reaches to 400–500 m depth, ie, far below the sill depth (270 m) of the Norwegian Trench (Rodhe, 1987).

The different currents contributing to Skagerrak water masses can be distinguished by their salinities (Rydberg *et al.*, 1996). The BC surface waters show salinities between 20 and 30 psu. The NJC, composed of a mixture of various North Sea as well as NwAC waters entering the Skagerrak from west and southwest, has values between 31 and 35 psu, whereas the deeper North Atlantic water-inflows from the counter current system of the Norwegian Trench possess salinities of > 35 psu. The salinity of Skagerrak surface waters

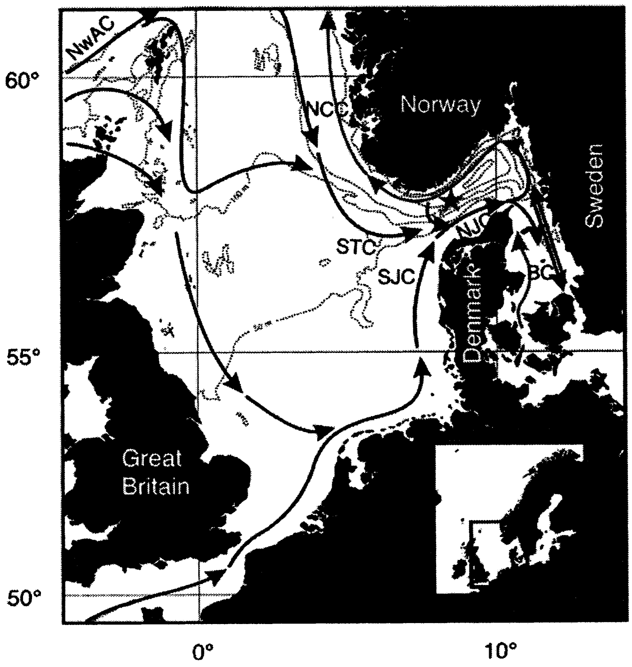

Figure 1 Map of the area of investigation, core location denoted by a star, hydrography following Nordberg (1991), solid arrows indicating deep currents, grey arrows indicating shallow currents. NwAC, Norwegian Atlantic Current; STC, Southern Trench Current; SJC, Southern Jutland Current; NJC, Northern Jutland Current; BC, Baltic Current; NCC, Norwegian Coastal Current

generally varies between 29 and 31 psu whereas the deeper water masses show values around 35 psu (Rodhe, 1987).

Deep-water renewal occurs during cold winters when the North Sea waters of the central North Sea Plateau are strongly cooled (Ljøen and Svansson, 1972). The strong cooling of central North Sea water masses results in water densities higher than in the Skagerrak and also higher than the densities of North Atlantic waters in the Norwegian Trench. Ljøen (1981) demonstrated that these high-density water masses cascade into the deeper parts of the Skagerrak, starting in January to February, on average every second to third year. A complete renewal seems to be accomplished in about four to five months.

Material and methods

Gravity core 225514 of 405 cm length was recovered with RV *Alkor* on Cruise 159. The sampling location (57°50′260″ N, 8°42′327″ E) is situated on the southern slope of the Skagerrak in 420 m water depth (Figure 1). The recovered sediments consist of olive-green clayey mud that frequently shows streaks of light grey colour (15–85 cm, 135–406 cm) throughout.

The core generally was sampled every 5 cm. To enhance the resolution of the youngest part of the core, in the uppermost 15 cm every centimetre was sampled and down to 80 cm core depth every second to third centimetre was sampled. Slices of 1-cm thickness were freeze dried and subsequently wet sieved to obtain the sediment fraction between 125 μm and 2 mm, which was used for all analyses described below. Bottom water from directly above the sediment/water interface was derived from one of the multiple corer tubes of sampling location 242940 (57°40′52″ N, 7°10′0″ E, 315 m water depth), which was sampled on RV *Poseidon* Cruise PO 282.

Isotopic investigation

The stable oxygen isotopic composition of tests of selected benthic foraminiferal species was determined with a Finnigan MAT 251 isotope ratio gas mass spectrometer directly coupled to an automatic carbonate preparation device (Kiel II). All values are given in δ-notation versus Vienna Pee Dee Belemnite (VPDB). For calibration to the VPDB scale the international standard NBS 19 was used. Overall precision of measurements based on repeated analyses of an internal laboratory standard (Solnhofen limestone) over a 1-yr period was better than 0.08‰.

For the determination of bottom water $\delta^{18}O$ of multiple corer 242940, 7 ml water were equilibrated in 13 ml headspace with CO_2 gas by using an automated Finnigan equilibration device. Isotope equilibrium in the CO_2–H_2O system was attained by shaking for 430 min at 20°C. The equilibrated gases were purified and transferred to an online-connected Finigan MAT Delta-S mass spectrometer. Isotope measurements were calibrated against Vienna Standard Mean Ocean Water (VSMOW) and Vienna Standard Light Antarctic Precipitation (VSLAP). Two replicates, including preparation and measurement, were run. Results are reported in δ-notation relative to the VSMOW scale with an external reproducibility of ±0.03‰.

Though $\delta^{18}O$ values of multiple species were measured, we only present values derived from *Bulimina marginata*, *Melonis barleeanum* and *Uvigerina mediterranea*. Individuals of these species seemed to be the least affected by carbonate dissolution and re-precipitation as inferred from microscopic and SEM investigations.

Palaeotemperature calculations were done applying the equation of Erez and Luz (1983):

$$t = 17.0 - 4.52(\delta^{18}O_c - \delta^{18}O_w + 0.03(\delta^{18}O_c - \delta^{18}O_w)^2$$

where t is the estimated bottom water temperature, $\delta^{18}O_c$ is the $\delta^{18}O$ value of shell carbonate, and $\delta^{18}O_w$ is the $\delta^{18}O$ value of sea water. Following Gonfiantini *et al.* (1995) the $\delta^{18}O$ value of bottom water (0.35‰ VSMOW) was converted to PDB scale by subtracting 0.27‰. Paleotemperatures were calculated without changing δ_w.

Though originally developed for planktic foraminifers the equation proved not only to be valid for benthic foraminifers but also as best fit to estimate palaeotemperatures of *Uvigerina peregrina* stable oxygen isotopic values (Bemis and Spero, 1998, and references herein). *Uvigerina peregrina*, which calcifies its test in equilibrium to bottom water $\delta^{18}O$ and therefore is used as approximation for equilibrium calcite, is not part of the benthic foraminiferal fauna of core 225514. Therefore we used individuals of *B. marginata*, which calcify their tests with an offset to bottom water $\delta^{18}O$, the so called 'vital effect'. Wilson-Finelli *et al.* (1998) determined an average value of 0.28‰ as being the vital effect of *B. marginata*. For determination of this vital effect these authors used the temperature equation of Shackleton (1974). Since the temperatures presented in this publication are based on the equation of Erez and Luz (1983) we recalculated the vital effect determined by Wilson-Finelli *et al.* (1998) using the equation of Erez and Luz (1983). The resulting vital effect of 0.24‰ was subtracted from measured $\delta^{18}O$ values of *B. marginata* prior to temperature calculation.

Age model

The age model for the investigated core was deduced from core III KAL (Hass, 1996) by faunal comparisons. Core III KAL originates from the southern flank of the Skagerrak and was taken only 150 m away from the location of core 225514.

Initially, it was intended to date core 225514 by AMS ^{14}C dates on bulk benthic foraminiferal tests (Table 1). Measurements were done at the Leibniz-Labor for Radiometric Dating and Isotope Research in Kiel. Measured values were corrected for the natural isotope fractionation. Calibration and transformation to calendar years was done by applying the radiocarbon calibration program Calib rev. 4.3 (Stuiver and Braziunas, 1989). We used the marine model calibration curve (Stuiver and Braziunas, 1989) together with the global reservoir age of about 400 years ($\Delta R = 0$). By comparing dominant benthic foraminiferal species of core 225514 with the dominant species described by Hass (1997), it became obvious that the faunas showed excellent co-variation if plotted against core depth (Figure 2). The corresponding age models, however,

Table 1 Conventional and to calendar years calibrated AMS ^{14}C dates on bulk benthic foraminiferal tests of core 225514

Core depth (cm)	AMS ^{14}C age	Stand. dev. AMS ^{14}C age	Cal. BP
0–3	(> AD 1954)		0
9–12	810	30	460
39–42	1155	30	690
69–72	1205	30	730
104–107	1165	30	1310
134–137	2710	+30/ – 35	2350
154–157	2755	45	2450
249–252	4280	45	4400
309–312	6400	45	6090
374–377	5680	45	6870

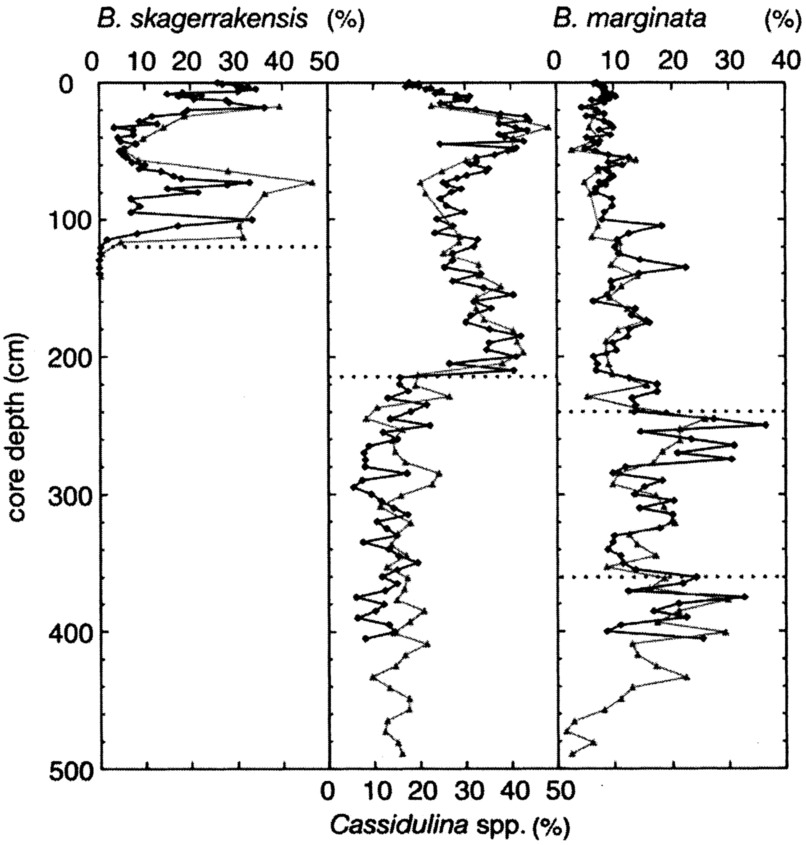

Figure 2 Core depth to frequency relation of selected species in percent of the total benthic foraminiferal fauna (solid diamonds) in comparison with frequencies Hass (1996) observed in core III KAL (grey triangles). Ordinates correspond to core 225514 since core III KAL presumably misses the top (last 17 cm)

diverged by up to 2500 years (Figure 3). There are several technical reasons why AMS ^{14}C based age models for deep Skagerrak sediments could be erroneous. Since there was not sufficient material for mono-specific dating, we were forced to use bulk benthic foraminifera. Heier-Nielsen *et al.* (1995) dated single species of benthic foraminifera as well as mollusc shells from the same depth intervals of sediment cores from the Danish Skagerrak slope. They found age discrepancies of up to 5000 years, which were attributed to re-sedimentation of single benthic foraminiferal species, as for example, species of the Miliolidae group. The conversion to calendar years could be another reason for incorrect age determinations by AMS ^{14}C measurements, since radiocarbon plateaus could cause errors of up to several centuries. One of these radiocarbon plateaus, for example, exists around 2500 cal. BP (calendar years before present) (Guilderson *et al.*, 2005).

Though we only present results of the last 1000 years or 190 cm, which correspond to the time range for which NAO reconstructions exist, core 225514 spans 405 cm. To prove that faunal compositions of core III KAL and 225514 are very close and that therefore it is valid to transfer the age model of Hass (1996) to core 225514, Figures 2 and 3 show the whole core depth.

Hass (1996) determined the age model for core III KAL based on an advanced ^{210}Pb method (Erlenkeuser, 1985a), which allows dating until approximately 3500 cal. BP. Sediments younger than 160 years were dated using the 'excess ^{210}Pb' method. Older sediments were dated with help of the '^{226}Ra supported ^{210}Pb' method ($^{210}Pb_{sup}$) following Erlenkeuser (1985a). For detailed information about the method and the model see Hass (1996).

Comparisons of dominant benthic foraminiferal species were used to tie the age model of core III KAL (Hass, 1996, 1997) to core 225514. The distance between both core locations accounts for only 150 m and both cores originate from similar water depths (225514 from 420 m, III KAL from 450 m water depth). Comparisons of the most important benthic foraminiferal species revealed very similar frequencies in corresponding depth intervals (Figure 2) if the top of core III KAL was shifted down-core for 17 cm. Obviously, core III KAL misses the top, possibly because of the loss of the topmost sediments during the sampling procedure.

Control points for the correlation between both cores were chosen where major changes in the three most frequent species, *Bulimina marginata*, *Cassidulina* spp., and *Bolivina skagerrakensis* occur, that is at 120, 215, 240 and 360 cm core depth. Generally, these major changes coincide to the centimetre; the first occurrence of *B. skagerrakensis* only seems to be earlier in core III KAL (126 cm core depth) than in the investigated one (120 cm core depth). This difference can be explained by the fact that the sampling interval of Hass (1996) is larger than the one we used and therefore sample resolution is lower. The most important faunal changes, however, coincide very well. The ages of the topmost 17 cm, which are missing in core III KAL, were linearly extrapolated. For the oldest parts of the core no corresponding ages of III KAL are available, since the $^{210}Pb_{sup}$ method is only valid until roughly 3500 cal. BP.

We chose the age model of Hass (1996) based on the $^{210}Pb_{sup}$ method, because our temperature reconstructions did not fit to any published climate reconstruction of this area when we used the ^{14}C AMS age model. Based on AMS ^{14}C dating, reconstructed temperatures in the 'Little Ice Age', for example, would have been the warmest reconstructed temperatures of the whole core.

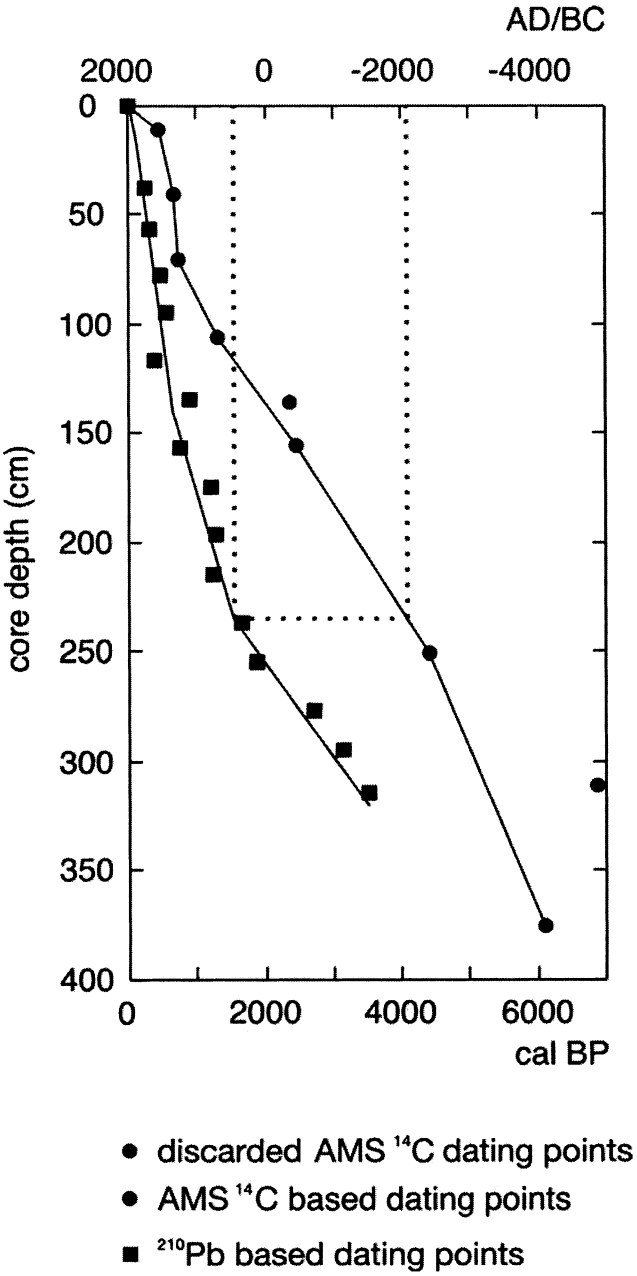

Figure 3 Age–depth relation of ^{210}Pb-based (solid squares) and ^{14}C AMS based (solid circles) age model. Grey circles denote ^{14}C AMS-based dating points, which were discarded as they were considered to show ages that were too old (see text)

Results

We present the $\delta^{18}O$ measurements of *Bulimina marginata*, *Uvigerina mediterranea* and *Melonis barleeanum* (Figure 4). In the discussion, however, we will focus on the results of *B. marginata*. The $\delta^{18}O$ values of *M. barleeanum* and *U. mediterranea* are presented to show that *B. marginata* was not subject to re-sedimentation processes. Though all curves exhibit a strong scatter and show markedly different mean values, the latter of which can be attributed to species-specific vital effects, in general they show the same evolution. Smaller differences amongst all curves can be ascribed to the sample interval of 1 cm, which comprises foraminifers of several years each. In the upper part of core 225514 (190–0 cm) investigated here the range of $\delta^{18}O$ variation accounts for 0.57‰, between a minimum value of 2.55‰, and a maximum value of 3.12‰ (Figure 4).

From 190 to 145 cm $\delta^{18}O$ values are generally comparably low but show a trend to increasing values. Between 145 and 75 cm core depth there is a trend to increasing values. The general trend is interrupted by two episodes with higher values (140–130 cm, 120 cm). Though generally regarded as a period of lower values, the depth interval 75 to 25 cm shows very variable $\delta^{18}O$ values and also highest recorded $\delta^{18}O$ values are found in this depth interval (35 cm core depth). From 25 cm core depth to the top, $\delta^{18}O$ values show a strong decrease to lower values.

The estimated temperature range is 4.2 to 7.1°C (Figure 4). The curve behaves like the $\delta^{18}O$ curve described above. Low values are translated in high temperatures, high values in low temperatures.

Discussion

Deep-water renewal in the Skagerrak

Generally, $\delta^{18}O$ values recorded in benthic foraminiferal tests are a product of two influencing parameters: (1) the temperature of the water mass in which the investigated foraminifers calcified their tests, and (2) δ_w, which corresponds to salinity and global ice volume. The global ice volume as influencing parameter can be ignored because the ascending of the sea level after the last glacial maximum was levelling out around 7000 cal. BP (Fairbanks, 1989; Bard *et al.*, 1989; Lambeck *et al.*, 2004) and therefore the general oxygen isotopic composition of the world ocean has not changed significantly (around 0.05‰ according to Fairbanks 1989) during the time interval in question.

It is difficult to distinguish the respective influence of temperature and salinity on $\delta^{18}O$ values. This is especially true for the Skagerrak area because of its complex hydrography. Water masses originating from the southern and central North Sea, the North Atlantic and the Baltic Sea enter this basin and are mixed to a certain degree. This is the reason why neither water temperatures nor salinities can be estimated easily. However, hydrographical measurements at different water depths of various regions of the Skagerrak over a time range from 1947 to 1999 do exist (ICES Oceanographic Database and Services; Ljøen, 1981; Grip *et al.*, 1993). From these data temperature variations between 3.5 and 7.5°C and salinity variations between 34.9 and 35.2 psu at 400 m water depth can be deduced.

Mikalsen and Sejrup (2000) constructed a salinity–$\delta^{18}O$ mixing line for the waters of the Sognefjorden, which they suggest to be valid for intermediate and basin waters in western Norwegian fjords. They found a 0.31‰ change in $\delta^{18}O$ values per 1 psu salinity change. Therefore, a maximum range of 0.3 psu salinity change accounts for maximum 0.09‰ of the $\delta^{18}O$ variance in modern Skagerrak deep waters. Since the total $\delta^{18}O$ variability over the whole core depth is about 1‰, the salinity changes are responsible for maximal 9% of this variability. Furthermore, temperature and salinity influence $\delta^{18}O$ values in opposite directions, so that the resulting temperature signal has to be regarded even as underestimated. Besides, the maximum $\delta^{18}O$ variability induced by salinity changes lies within the error margin of our measurements (±0.08‰). Hence, we conclude that the observed $\delta^{18}O$ variability in benthic foraminiferal tests from the deep Skagerrak mainly reflects water temperature changes.

Reconstructed palaeotemperature estimates range from 4.2 to 7.1°C. This range lies within the recorded modern temperature range between 3.5 and 7.5°C at 400 m water depth.

Sudden drops, both in temperature and salinity in the deep Skagerrak during modern times (Figure 5) point to advection-induced cascades of central North Sea waters (Ljøen and Svansson, 1972; Ljøen, 1981; Ivanov *et al.*, 2004). After deep-water renewal has been accomplished, temperatures and salinities slowly ascend over a time period of two to three years, indicating thermohaline mixing with overlying warmer and more saline North Atlantic waters.

In general, the short time intervals of two to three years are not resolvable within our sedimentary record. The average timespan between the samples accounts for 17 years. The sediment slices of 1-cm thickness used comprise foraminifers of a timespan of 4 and 9 years in the youngest 565 years and before, respectively. Consequently, the $\delta^{18}O$ values determined have to be regarded as mixed signals that underestimate the total temperature range. Nevertheless, the strongly scattered data clearly show maximum and minimum temperatures, even though masked by mixing. In summary, we suggest that high $\delta^{18}O$ values, as representing low water temperatures, mirror Skagerrak deep-water renewal in late winter to spring time as a result of advection-induced cascades of dense water masses from the central North Sea.

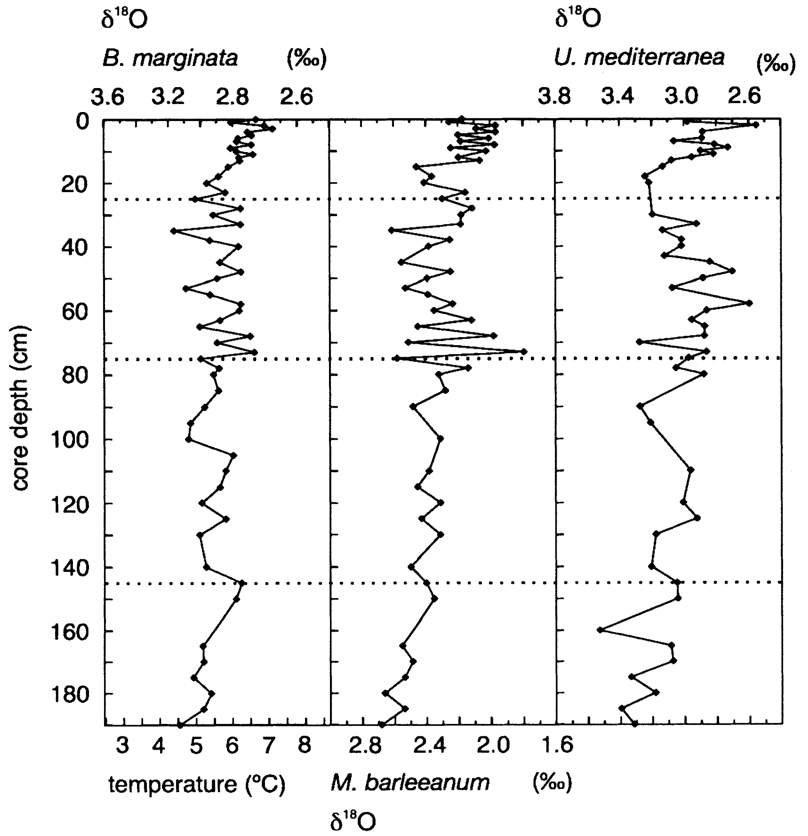

Figure 4 Measured $\delta^{18}O$ values/reconstructed temperatures as a function of core depth of *B. marginata*, *M. barleeanum* and *U. mediterranea*. Dotted lines indicate intervals of higher and lower $\delta^{18}O$ values as described in the text. Temperature estimates were calculated from vital effect-corrected $\delta^{18}O$ values of *B. marginata* according to the equation proposed by Erez and Luz (1983)

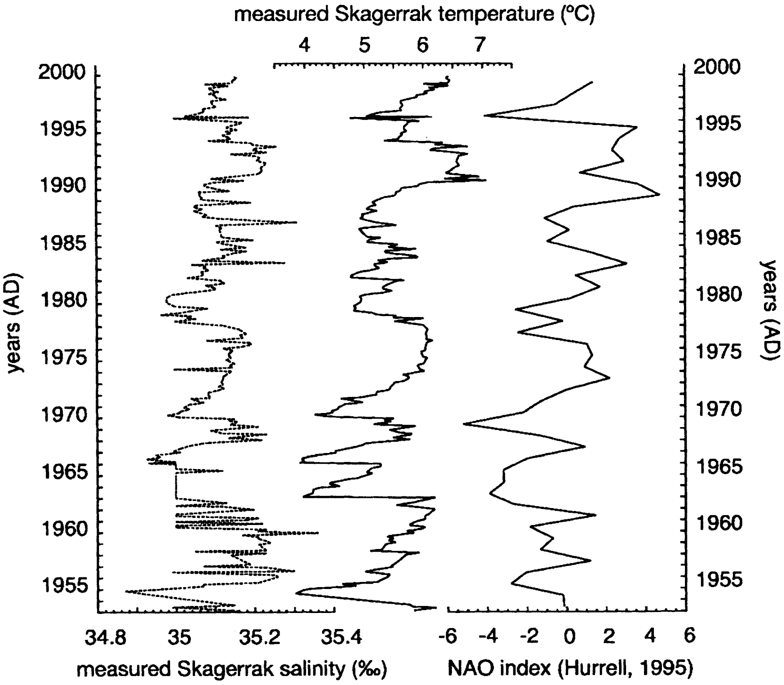

Figure 5 Evolution of Skagerrak salinity (left curve), deep-water temperature (middle curve) and annual NAO index (Hurrell, 1995) (right curve) during modern times

Relationship to the North Atlantic Oscillation

Short-term variability

Deep-water renewal in the Skagerrak usually starts in January/February and is accomplished four to five months later, ie, it is initiated during the season of strongest NAO forcing (December to March). Power spectrum analysis of the annual NAO index has revealed that dominant periods of the NAO variability are 6 to 10 years and 2 to 3 years (Hurrell and van Loon, 1997; Chen and Hellström, 1999), the latter coinciding with the modern Skagerrak deep-water renewal interval Ljøen (1981) described.

A feasible mechanism leading to Skagerrak deep-water renewal triggered by the NAO will be described as follows: During predominantly negative NAO index winters westerlies are weak and their track is shifted further to the south in a more W–E direction over central and southern Europe into the Mediterranean. Northern Europe experiences frequent blocking situations, which in turn allow severely cold and dry conditions from northern Scandinavia/Russia to take influence over northern Europe (Koslowski and Glaser, 1999). These unusually low temperatures result in a strong cooling of shallow central North Sea waters, which therefore reach higher densities than the waters of the deep Skagerrak. Advection-induced deep-water renewal in the Skagerrak follows.

During predominantly positive NAO index winters the pressure gradient between Islandic low and Azores high is unusually high, storm frequency and intensity is enhanced. The storm track shifts to a more northeasterly direction (Rogers, 1997). This results in temperatures above the average and extremely stormy winter conditions over northern Europe, not allowing central North Sea waters to reach the necessary densities (which in this case is mainly a function of temperature) to substitute Skagerrak deep waters. During these time intervals, Skagerrak deep waters successively increase in temperature and salt content by thermohaline mixing with overlying warmer and saltier North Atlantic water masses. The positive correlation between the temperature evolution of Skagerrak deep waters and the NAO during the time period AD 1970–1994 was recognized earlier by Hagberg and Tunberg (2000). Correlation analysis of the temperature and NAO index data shown in Figure 5 revealed that this relationship existed at least since AD 1950. The correlation coefficient between the annual NAO index and adjusted deep-water temperatures is 0.75. The time frame of the deep-water temperature had to be adjusted since there is a time lag of up to two years between the negative phase of the NAO and the triggered deep-water renewal (Hagberg and Tunberg, 2000). These time lags strongly affect the correlation coefficient between the NAO index (Hurrell, 1995) and modern Skagerrak deep-water temperatures. Since the NAO index always precedes the deep-water renewal, a shift of maximal two years to older ages was allowed. Subsequently, we re-sampled the data to achieve equal time intervals. Without adjustment a correlation coefficient of only 0.46 would be reached.

It has been suggested that the origin of Skagerrak deep waters lies within the NwAC, a side branch of which enters the Skagerrak via the Norwegian Trench (eg, Erlenkeuser, 1985b; Hass, 1996). There is, however, a reason why this supposition is not very probable: Orvik *et al.* (2001) found a strong coupling between the strength of the westerly winds as an expression of the state of the NAO and the inflow of North Atlantic waters via NwAC's eastern branch into the Norwegian Sea. In general, high inflow events coincide with positive NAO index values. So there actually is a correlation between the NAO and the amount of NwAC waters entering the Norwegian Sea via the eastern branch of NwAC. Renewed Skagerrak deep waters, however, are characterized by both comparably low temperatures and salinities. During modern times these low temperatures and salinities are not common in the shallow waters of the NwAC (Mork and Blindheim, 2000), which feed the side branch that enters the Skagerrak via the Norwegian Trench. Therefore, we conclude that the main source of Skagerrak deep waters is the central North Sea and not the Norwegian Sea. Consequently, temperature-induced density differences between Skagerrak deep waters and central North Sea waters provide the basis for deep-water renewal in the Skagerrak. Temperature, in turn, is also the physical property in which

NAO changes are expressed in benthic foraminiferal $\delta^{18}O$ data. Therefore, the strong scatter of $\delta^{18}O$ values mirrors the short-term variability of the NAO as it represents the temperature drops that reflect deep-water renewal.

Long-term variability

In the following we will demonstrate that the long-term variability of the data we present mirrors long-term frequencies of the NAO. Proctor *et al.* (2000) reconstructed precipitation amounts for the last 1100 years by growth rates of stalagmites from a cave in northwestern Scotland. They showed that precipitation amounts are strongly coupled to the state of NAO winter index (Hurrell, 1995), being high during positive NAO phases and *vice versa*. Their results are important because their data go further back in time than those reconstructed from tree-rings and ice cores (Appenzeller *et al.*, 1998; Cook *et al.*, 1998). The data of Proctor *et al.* (2000) explain 50% of the winter NAO's variance. This percentage of explained variance is even higher than that of tree rings (33%) and ice cores (41%).

Our temperature reconstructions from the deep Skagerrak and reconstructed precipitation amounts from northwest Scotland (Proctor *et al.*, 2000) show a close relationship regarding their long-term variability (Figure 6). Low precipitation amounts and low temperatures herein reflect negative NAO phases whereas high precipitation amounts and high temperatures are connected to positive NAO phases. Note the different time resolution of the two proxies. Precipitation amounts are recorded on an annual basis and therefore mirror NAO very precisely, whereas the data of core 225514 show mixed signals of several years.

It has been speculated if low frequency changes of the NAO could be capable of influencing climate on long timescales. It was suggested that the climax of LIA winters over northern Europe was the result of predominantly negative NAO index winters (Koslowski and Glaser, 1999; Proctor *et al.*, 2000; Shindell *et al.*, 2001), and that the MWP has a predominance of positive NAO index values (Proctor *et al.*, 2000; Shindell *et al.*, 2001; Cook, 2003).

The LIA is the best-resolved time interval of the data presented here and therefore basically will be used to investigate the above-mentioned speculation. In contrast to the speculations of Koslowski and Glaser (1999), Proctor *et al.* (2000) and Shindell *et al.* (2001) we cannot detect an indication for generally lowered temperatures, regardless of where one would like to define the climax of LIA, which could be interpreted as the NAO being in a predominantly negative phase. What we do find is a period of very unstable conditions. The range of temperature variation is higher than during the following period leading to modern conditions. Temperature differences between central North Sea winter waters and North Atlantic waters overlying Skagerrak deep waters are very high. The preceding time interval of the MWP has a much lower sample density, but shows, as during the LIA, large amplitude variations. This is why we are not able to deduce the LIA as exceptional compared with the MWP. It is exceptional however, compared with the transitional phase to modern times.

A possible explanation for these strong temperature differences during the LIA is provided by Berstad *et al.* (2003). These authors state a deepening of the NwAC during the early LIA (approximately AD 1400–1650) compared with the period AD 1750–1950. They further speculate that thermohaline circulation was decelerated in the early LIA and enhanced in the latter part. In our data, NwAC water masses are represented by the comparably warmer temperatures within the short-term variability. After a deep-water renewal event the cold and low saline deep waters mix with overlying NwAC-derived water masses, which are warmer and saltier. Our

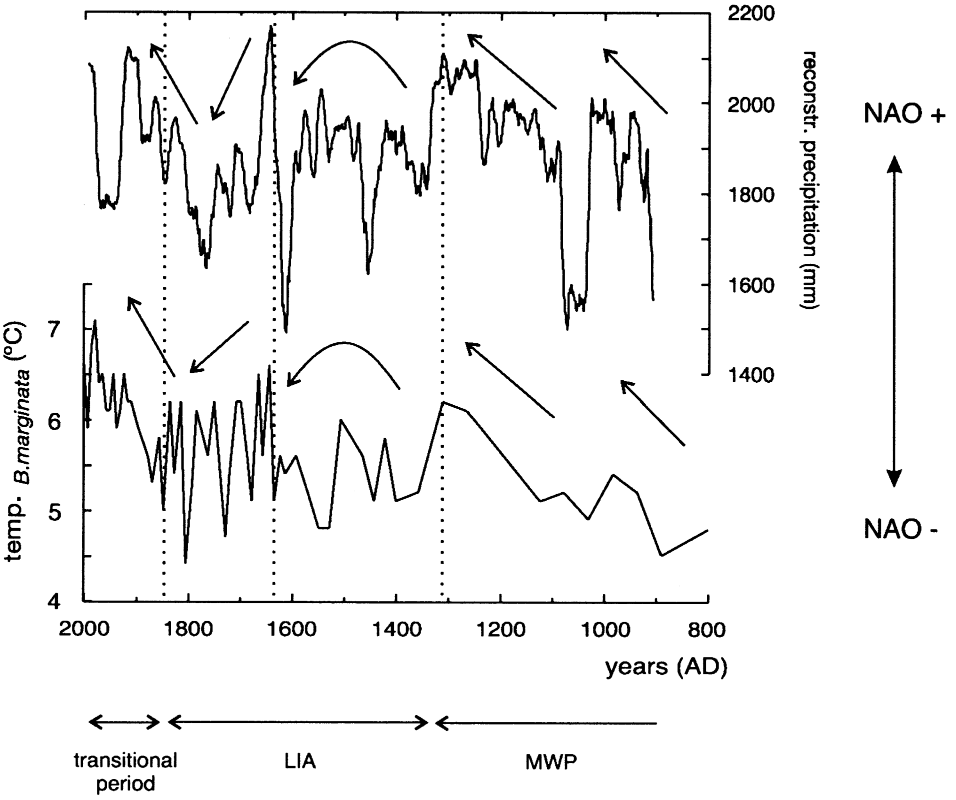

Figure 6 Temperature estimations of Skagerrak deep waters and reconstructed precipitation amounts from northwest Scotland (Proctor *et al.*, 2000). Low temperatures and little precipitation correspond to negative NAO phases and *vice versa*. Dotted lines indicate periods discussed in the text. Curved arrows indicate the general evolution during certain time intervals discussed in the text

palaeotemperature reconstructions display comparably cold conditions until AD 1630, which coincides with a decelerated thermohaline circulation, bringing less warmth to the Northern Hemisphere. The period AD 1630–1870, which is characterized by high temperature differences between North Sea winter waters and overlying warm NwAC-derived water masses, falls into the time period of accelerated thermohaline circulation. The heat transport to the Northern Hemisphere is enhanced, which explains the comparably warm North Atlantic water temperatures indicated by temperature reconstructions of core 225514. Contemporaneously recorded low temperature excursions could be the result of frequently occurring deep-water renewal episodes during strongly negative, but short-lasting NAO phases.

Conclusions

We investigated a sediment core from the southwestern flank of the deep Skagerrak (420 m water depth) for the stable isotopic composition of its benthic foraminiferal tests. We show that $\delta^{18}O$ measurements on benthic foraminiferal tests from deep Skagerrak mainly reflect temperature variations of the bottom water mass.

As stated by Hagberg and Tunberg (2000), Skagerrak deep-water temperatures of the last 30 years correlate with the NAO winter index. Deep-water renewal is triggered by the negative phase of the NAO. We show that this is the case for at least the last 50 years. The correlation between adjusted modern Skagerrak deep-water temperatures and the annual NAO is good ($r = 0.75$).

The origin of deep Skagerrak waters presumably is the central North Sea and not the Norwegian Sea. Modern temperature and salinity measurements show that winter-water densities in shallow to intermediate depths of the eastern branch of the Norwegian Atlantic Current are not high enough to replace Skagerrak deep water.

$\delta^{18}O$ values measured on benthic foraminiferal tests of the deep Skagerrak reflect the state of the NAO during the last 1200 years. A close relationship between $\delta^{18}O$-derived Skagerrak deep-water temperatures and reconstructed precipitation amounts from northwestern Scotland, which were shown earlier to closely mirror the NAO, is demonstrated.

We cannot reinforce the speculation concerning the NAO influencing climate by predominantly staying in one phase. 'Little Ice Age' data do not mirror constantly lowered temperatures in the Skagerrak during this time interval. However, they indicate high temperature differences between central North Sea winter waters and overlying warmer North Atlantic water masses. These temperature differences might be the result of the combination of a generally accelerated thermohaline circulation and frequently occurring deep-water renewal episodes resulting from strongly negative, but short-lasting NAO phases.

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