Paleoceanography of the North Atlantic Ocean (68°-76°N) during the past 450 ky deduced from planktic foraminiferal assemblages and stable isotopes

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ABSTRACT
Polar and subpolar planktic foraminifera and the stable oxygen and carbon isotopes of Neogloboquadrina pachyderma (s) from the Nordic seas are analyzed for the time period since oxygen isotope Stage 12, with special emphasis on interglacial time slices Stages 11, 5e (Eemian), and 1 (Holocene).

A comparison of relative (%) and absolute test concentrations from two different size fractions reveals a complex downcore pattern for the morphogroup N. pachyderma. Ratios of small-sized N. pachyderma (s) to N. pachyderma (d) vary between Stage 11, the Eemian and the Holocene, due to changes in test concentrations of N. pachyderma (s) only. As revealed in the downcore records, both coiling varieties of N. pachyderma are somehow related to each other, but the use of percent data as surface water mass proxy appears to be limited. The most dominant subpolar species, Turboquadratina quinqueloba and Globigerina bulloides, mainly occurred during the Holocene, the Eemian, and Stage 11. Both species are inversely related to N. pachyderma (s) in that their abundances steadily increased during all three interglacials. During these times, C. bulloides remained always restricted to the eastern area of the Nordic seas with dominant Atlantic water masses. In contrast T. quinqueloba exhibited a much wider distributional pattern.

From stable isotopes and faunal variability it is inferred that the entire Nordic seas was covered by sea-ice during the cold seasons in Stage 11 resulting in both, highest test concentrations of N. pachyderma (s) and highest δ13C values observed throughout the past 450 ky. For the last two interglacials, oxygen isotope values and test concentrations of T. quinqueloba indicate that warmer surface waters must have prevailed in the western Iceland Sea in the Eemian compared with any time during the Holocene time interval.

INTRODUCTION
Recognizing variations of past water mass compositions has been a major issue for paleoceanographical and ultimately also for paleoclimatological interpretations. The climate over the past 600 ky has been dominated by strong fluctuations in northern hemisphere ice sheets (Tiedemann et al., 1994). During times of retreat and advance of the ice sheets, modern-type circulation patterns evolved and/or deteriorated accordingly. The timing of these glacial-interglacial cycles, reflected in the oxygen isotope record as global ice volume effect, has been tied to variations in solar radiation (e.g. Imbrie et al., 1984; Martinson et al., 1987). Based on the Milankovich theory, these orbitally induced changes (Hays et al., 1976) have left their imprint on northern high-latitude sediments. The close vicinity of the Nordic seas (Norwegian, Greenland, and Iceland seas) to repeatedly glaciated landmasses makes this area a key region to monitor late Pleistocene water mass/climate relations, which become particularly apparent during the change

from a glacial to an interglacial climatic mode (Imbrie et al., 1993). Previous faunal studies carried out in this region have shed some light on distributional patterns by assigning distinct species to belong to either a glacial or an interglacial fossil assemblage (e.g., Kellogg, 1984; Streeter et al., 1982; Haake & Pflaumann, 1989). Kellogg (1976, 1977, 1980) first documented the strong climatic and oceanographic resemblance of the last interglacial optimum, isotope Stage 5e, with that of the Holocene and stated that only these periods where times of full interglacial conditions (i.e. Holocene-like) whereas the others were marked by cool or cold conditions with ice-cover. However, this statement is strongly dependant on discriminating between ‘warm’- and ‘cold’-water indicating species of planktic foraminifera. But these earlier interpretations were based on different methodologies, i.e. in terms of the lower limit of the used mesh size, which particularly during colder periods may not cover all of the ‘warm’ signal contained in the faunal record (Bauch, 1994a).

The purpose of this study is to show the temporal and spatial distribution of planktic foraminifera throughout the past 450 ky of glacial and interglacial change and to evaluate particularly the most prominent interglacials according to their oceanographic characteristics. It has been shown that of all interglacial phases during the past 450 ky, only the Holocene, Stage 5e and Stage 11 were prolonged times when the deposition of iceberg-rafted detritus (IRD) ceased in at least the southern Nordic seas (Birgisdottir, 1990; Baumann et al., 1995). Core sections covering interglacial Stages 7 and 9 contain notable amounts of IRD in the Nordic seas (Henrich et al., 1989). They, therefore, cannot be addressed as interglacials sensu stricto.

SURFACE WATER PROXIES

The modern surface water pattern of the Nordic seas may be characterized today by a threefold subdivision based on salinity variations and temperatures which decrease towards the north and the west (Swift, 1986). Incoming relatively warm and high saline Atlantic surface water (6-10°C, >35‰) that flows as the Norwegian Current (NC) along Norway’s and Svalbard’s shelf margin towards the north into the eastern Arctic Ocean basin comprises the Atlantic Domain (Fig. 1). The western part of the Nordic seas, made up of the Polar Domain, is marked by the outflow of the relatively cold and low saline water (<0°C, <34.4‰; Swift, 1986) of the East Greenland Current (EGC) from the Arctic Ocean. This water eventually leaves the Nordic seas via Denmark Strait into the North Atlantic. Polar and Atlantic domains are separated from each other by the Arctic Domain.
Paleoceanography of the North Atlantic Ocean (68°-76°N) during the past 450 ky

Table 1. Geographical position, water depth, and modern surface water temperatures (adopted from Dietrich, 1969) of investigated core sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Geogr. Position</th>
<th>Water Depth</th>
<th>Core Length</th>
<th>Modern Temp. °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>M17732</td>
<td>71°36.8' N</td>
<td>3103</td>
<td>5.93</td>
<td>8.0</td>
</tr>
<tr>
<td>M23055</td>
<td>68°25.4' E</td>
<td>2311</td>
<td>6.67</td>
<td>9.5</td>
</tr>
<tr>
<td>M23063</td>
<td>68°45.0' E</td>
<td>2299</td>
<td>9.18</td>
<td>8.5</td>
</tr>
<tr>
<td>PS1243</td>
<td>69°22.3' W</td>
<td>2710</td>
<td>7.67</td>
<td>8</td>
</tr>
<tr>
<td>PS1244</td>
<td>69°22.0' W</td>
<td>2162</td>
<td>6.68</td>
<td>7.5</td>
</tr>
<tr>
<td>PS1246</td>
<td>69°23.6' W</td>
<td>1902</td>
<td>7.09</td>
<td>5.0</td>
</tr>
<tr>
<td>PS1906</td>
<td>76°50.1' W</td>
<td>2939</td>
<td>6.53</td>
<td>3.5</td>
</tr>
</tbody>
</table>

which essentially is mixed water from the former two. Moreover, this domain is the main area of deep water formation in the Nordic seas and has two distinct oceanographic fronts on either side.

Various planktic faunal and floral investigations are instrumental in monitoring the variability of oceanic processes in the Nordic seas during glacial to interglacial time (e.g. Kellogg, 1980; Jansen & Bjorklund, 1985; Baumann & Matthiessen, 1992; Bauch, 1993). A particular marine microfossil assemblage can either serve as a direct indicator of the past surface water or can be utilized to estimate specific physical properties, e.g. temperature (Koç-Karpuz & Jansen, 1992). Within marine planktonic assemblages, which are believed to be good recorders of present and past physical and chemical surface water changes, planktic foraminifera in particular represent a major component in the deposition of hemipelagic and pelagic sediments, resulting in high amounts of carbonate content in the sediments (Kellogg, 1975; Baumann et al., 1993). Traditionally, all species that occur in upper Pleistocene or Holocene sediments in the North Atlantic may be assigned, according to their generally preferred latitudinal habitat, to a polar and a subpolar group (Kipp, 1976; Kennett & Srivivasan, 1983; Hemleben et al., 1989), and consequently, to a glacial or interglacial group. In the Nordic seas left-coiled Neogloboquadrina pachyderma sinistral (s) is the main representative of the polar group. Although often regarded as the only true polar species, it is well known that N. pachyderma (s) is to some extent always accompanied by the right-coiled variety N. pachyderma dextral (d). The subpolar group is predominantly made up of Turborotalita quinqueloba, Globigerina bulloides, Globigerinita glutinata, Gl. umbilica and depending on the water mass temperatures also of N. pachyderma (d). To a much lesser degree, even species from temperate or subtropical provenances do occasionally occur (Kellogg, 1984; Haake & Pflaumann, 1989). However, most of these species are rare and appear to be restricted to the Eemian time interval and the southeastern part of the Nordic seas where the influence of North Atlantic surface water is most dominant (Kellogg, 1980; Bauch, 1993). Stratigraphically, subpolar foraminifera occur in the Nordic seas mainly during interglacial times and are, therefore, indicative for the presence of warm Atlantic water. Because of its nearly continuous presence in both glacial and interglacial high-latitude sediments, the polar species N. pachyderma (s) is most commonly used for stable isotope analyses, thus providing the downcore stratigraphical framework.

MATERIALS AND METHODS

For this study six sites were chosen, which on a broad scale cover the main water masses of the Nordic seas (Fig. 1). Most of these cores are spliced together with box cores from the same site and originate from water depth ranging between ~1900-3100 m (Table 1). All cores were collected during cruises of the German research vessels RV Polarstern and RV Meteor.

Sampling of the cores was carried out as 1 cm thick slices at intervals of 5-10 cm for the long cores and usually every 2 cm for the box cores. All samples for faunal investigations were then dried, weighed, washed into >63 μm residues and later separated into different size fractions (63-125 μm, 125-250 μm, 250-500 μm, >500 μm). For counting the planktic fauna a mesh size range of 125-500 μm was considered. The use of the size fraction > 125 μm has proven to be a crucial issue for evaluating past oceanographic changes as planktic foraminiferal tests appear to be smaller in Nordic seas sediments than further south in the North Atlantic. Taking mesh size 150 μm as a lower limit, as recommended by CLIMAP Members (1976), may not give a fair reflection of relative species abundances. This in particular applies to the most abundant but relatively small-sized subpolar species in the Nordic seas, Turborotalita quinqueloba, which may bear important paleoceanographic implications for interpreting periods with changes in surface water properties (Bauch, 1994a; Hebbeln et al., 1994).
Faunal counts were carried out separately on the 125-250 μm and 250-500 μm fractions. With this method the abundance variations of larger-sized species such as, e.g., Globigerina bulloides can be better expressed, which would otherwise appear to be statistically underestimated in terms of their paleoceanographic implication. Prior to quantifications each appropriate sample was split down by means of a microsplitter. Test concentrations are expressed as specimens per gram dry bulk sediment.

Stable isotope measurements were performed on the species Neogloboquadrina pachyderma sinistral (s) using a fully automated MAT 251 mass spectrometer (Leibniz Laboratory at Kiel University). To reduce the effects of stable isotope differences among morphotypes of this common species (Healy-Williams, 1992), 25-30 four-chambered, quadrate specimens from the 125-250 μm size fraction were picked. The stratigraphical framework of the cores is based on the correlation between stable isotope records given by N. pachyderma (s) and the SPECMAP time-scale with its assignment of oxygen isotope stages and substages (Imbrie et al., 1984; Martinson et al., 1987). Stage boundaries were always set along the decreasing or increasing slopes of the oxygen isotope curves and, where necessary, further aided by the faunal results.

RESULTS
Stable isotopes
The stratigraphic control of the investigated sediment cores is based on both oxygen and carbon stable isotopes. This framework is further supported by the faunal results. Core PS1244 has no stable isotope record, but, as it will be shown in this study, it nevertheless has a good stratigraphical control due to faunal correlations with nearby Core PS1243. Furthermore, both cores correspond well in terms of CaCO₃ content (Birgisdottir, 1990). The isotope records date back to oxygen isotope Stage 12 for most cores (Fig. 2). Core M17732 extends stratigraphically down to approximately stage boundary 6/5 (Termination II). Despite the relatively low sample resolution, major features of the stable isotope records can be recognized in the cores. Interestingly, most often the carbon isotope record appears to be a more precise stratigraphical tool than the oxygen isotopes are. This in particular applies to Core PS1906 in which the oxygen record is rather difficult to interpret on its own below glacial Stage 2. Cores M23063 and PS1243, which today are most closely to the main flow path of Atlantic surface water, show best the typical changes that shaped environmental conditions during the past 5 glacial/interglacial cycles. However, apart from these common features, there are some significant characteristics which can be traced throughout the records and others which seem to vary laterally. In all cores the increase of δ¹³C values after Stage 2 is always concurrent with a decrease in δ¹⁸O. Highest Holocene carbon values are very similar in most cores ranging between 0.7-0.9‰. Core M17732 is lacking the uppermost 4 ky (Weinelt, 1993). In comparison peak values of the oxygen isotopes show much larger deviations, essentially due to the effects of either temperature variations in the surface water and/or to an additional input of freshwater from melted icebergs (e.g. compare Cores PS1906 and PS1243), both leading to lower values. This finding appears to be in strong contrast to the carbon and oxygen values recorded during Stage 5. Surprisingly, the highest carbon values of similar magnitude recorded in the Holocene are not coeval with the lowest oxygen values of the last interglacial phase, which always appears during early Stage 5, that is Stage 5e (or the Eemian; Mangerud, 1989). Instead, the highest carbon values are noted much later during Stage 5, close to Stage 4, whereas Stage 5e values are indeed lower by about 0.5‰ in comparison to the Holocene.

Those parts in the cores which are assigned to Stage 11 show a very intriguing pattern in terms of the lateral distribution of stable isotopes. Cores M23063, PS1243, and PS1246 display their highest δ¹³C values in Stage 11, but, whereas the oxygen values of about 3‰ indicate typically interglacial-like low values at the sites from the Norwegian Sea (Cores M23063 and PS1243), Core PS1246 from the western Iceland Sea records values close to 4‰. The δ¹³C values in Core PS1906 during this time are lower in comparison to other stages of this core. But it should be noted that here the highest carbon values in Stage 11 slightly lag behind the lowest oxygen values. The same feature is also observed in Core PS1243, which for this time period seems to have the best sample resolution of all investigated cores. Despite the generally good stratigraphic agreement of Stage 11, there are some notable discrepancies among the cores concerning the proper position of the Stage 11/10 boundary, which could not be precisely determined with the present sample resolution.

In a previous study, the lowest part in Core PS1246 (~680 cm) has been assigned to Stage boundary 15/16 (Bauch, 1994b). This section is clearly not present in Cores PS1243 and M23063 and therefore it was not attempted to further subdivide this interval in Core PS1246.

Faunal distribution
It is beyond the scope of this study to discuss in detail any notable variation in faunal composition.
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Figure 2. Glacial-interglacial stable oxygen (black curve) and carbon (grey curve) isotope records of the past 12 oxygen isotope stages analyzed on *N. pachyderma* (s) (approx. 450 ky). Arrows mark the peaks of the three most dominant interglacial phases. During these intervals test concentrations of planktic foraminifera were high and input of ice-rafted rock fragments by icebergs lowest, essentially indicating similar surface water conditions.

that might occur during, e.g., the Holocene section which of course could give valuable information on smaller-scaled oceanographic changes (Bauch & Weinelt, 1996); these Holocene to last glacial core sections were sampled in closer intervals than the older core sections and are therefore hardly comparable. But the way a full-interglacial subpolar assemblage evolved after a glacial maximum is illustrated in Fig. 3 for the Holocene and the last interglacial, the Eemian. Both, Holocene and Eemian faunal records show variations, however, the highest abundances of all interglacial-indicating species, i.e. subpolar species, are always noted during IRD-free sections only. Of all subpolar foraminifera in Core M23055 *T. quinqueloba* totals ~40% and is by far the most dominant species. The
between 6-5 ky BP \(^{14}C\) within the main phase of the hypsithermal with the highest Holocene temperatures (between 8-5 ky BP according to Nesje & Kvamme, 1991). *Turbo* *rotula* quinqueloba once again dominates the subpolar fauna and moreover, makes up \(~65\%\) of the total assemblage during its peak at about 5 ky, whereas all other subpolar species do not even exceed 10\% altogether. Although not shown here, but worth mentioning is the fact that the faunal species composition of the Holocene and Eemian sections is generally more diverse within the eastern cores from the Voring Plateau and south of it, i.e. below the main track of Atlantic water (Bauch, 1993; Kellogg, 1980).

In the following section the glacial and interglacial distributional pattern of some of the more important species shown in Fig. 4a-f will be described for the time period since Stage 12.

**Polar record**

In this study the relative abundance of *N. pachyderma* (s) varies between 15-98\% (Fig. 4a-f). Highest percentages are clearly related to typically glacial periods in all cores, whereas the lowest values are found in Cores M17732 and M23063 during the Holocene. Both of these sites are located below the modern track of warm Atlantic surface water. There is a clear signal of right coiling specimens between 30-40\% in both size classes of Core M17732 during the Holocene. This is also seen in the Eemian section but with an enhanced relative dominance of the larger specimens over the smaller tests (17 to 40\%). A similar pattern is noted in Core M23063 where larger specimens of *N. pachyderma* (d) dominate over smaller specimens during the Holocene but even more so during the Eemian. At the same time the relative abundance of *N. pachyderma* (s) in both cores is increased during the Eemian compared to the

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**Figure 3.** Distribution of the most dominant planktic foraminiferal species in the Holocene and across the last interglaciation, Stage 5e. The stratigraphy of Core PS1243 is based on radiocarbon ages (reservoir corrected by 400 years) and adopted from Bauch & Weinelt (1996). The duration of Termination I and II, i.e., the deglacial phase which preceded the Holocene and Stage 5e interglacial maximum, is deduced from the downcore distribution of ice-rafted rock fragments (adopted from Bauch et al., 1996). The vertical shaded bars indicate the interglacial optimum in the Holocene and Stage 5e intervals when highest abundances of subpolar species are observed (numbers in parentheses refer to the top scale of the vertical axis).

remaining subpolar foraminifera only make up 18\% of the assemblage altogether. If one compares the Eemian assemblage with that of the Holocene, then again all subpolar planktic foraminifera increase in test concentrations during the late deglaciation and, despite some obvious variability throughout the Holocene, reach their peaks between 6-5 ky BP \(^{14}C\) within the main phase of the hypsithermal with the highest Holocene temperatures (between 8-5 ky BP according to Nesje & Kvamme, 1991). *Turbo* *rotula* quinqueloba once again dominates the subpolar fauna and moreover, makes up \(~65\%\) of the total assemblage during its peak at about 5 ky, whereas all other subpolar species do not even exceed 10\% altogether. Although not shown here, but worth mentioning is the fact that the faunal species composition of the Holocene and Eemian sections is generally more diverse within the eastern cores from the Voring Plateau and south of it, i.e. below the main track of Atlantic water (Bauch, 1993; Kellogg, 1980).

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Figure 4a. Downcore variability of the dominant planktic foraminiferal species. Shown are the faunal results of the two size fractions 125-250 µm and 250-500 µm in comparison to planktic oxygen isotopes (grey curve) and relevant isotope stages. Arrows on oxygen isotope curves indicate the three most dominant interglacial phases.
Figure 4b. Downcore variability of the dominant planktic foraminiferal species. Shown are the faunal results of the two size fractions 125-250 μm and 250-500 μm in comparison to planktic oxygen isotopes (grey curve) and relevant isotope stages. Arrows on oxygen isotope curves indicate the three most dominant interglacial phases.
Figure 4c. Downcore variability of the dominant planktic foraminiferal species. Shown are the faunal results of the two size fractions 125-250 μm and 250-500 μm in comparison to planktic oxygen isotopes (grey curve) and relevant isotope stages. Arrows on oxygen isotope curves indicate the three most dominant interglacial phases.
Figure 4d. Downcore variability of the dominant planktic foraminiferal species. Shown are the faunal results of the two size fractions 125-250 μm and 250-500 μm in comparison to planktic oxygen isotopes (grey curve) and relevant isotope stages. Arrows on oxygen isotope curves indicate the three most dominant interglacial phases.
Figure 4e. Downcore variability of the dominant planktic foraminiferal species. Shown are the faunal results of the two size fractions 125-250 μm and 250-500 μm in comparison to planktic oxygen isotopes (grey curve) and relevant isotope stages. Arrows on oxygen isotope curves indicate the three most dominant interglacial phases.
Figure 4f. Downcore variability of the dominant planktic foraminiferal species. Shown are the faunal results of the two size fractions 125-250 µm and 250-500 µm in comparison to planktic oxygen isotopes (grey curve) and relevant isotope stages. Arrows on oxygen isotope curves indicate the three most dominant interglacial phases.
Holocene. During the colder climate periods (Stages 3 and 4) N. pachyderma (s) is predominant. The further downcore record in Core M23063 reveals another notable drop in relative abundance of small-sized N. pachyderma (s) during early Stage 7 but with no response from the right coiling variety. This is only indicated in Stage 11 where N. pachyderma (d) records a slight increase.

If one compares relative abundances with test concentrations in Core M17732, the record of small-sized N. pachyderma (s) shows relatively constant values throughout, except for a significant decrease during the Eemian and the Holocene. In contrast N. pachyderma (d) indicates warm conditions during the Holocene and the Eemian whereas large-sized N. pachyderma (s) shows its peak abundances clearly after the Eemian (upper Stage 5) during Stage 4 and with one obvious increase in Stage 3. The test concentration record of small-sized N. pachyderma (s) and N. pachyderma (d) below Stage 5 is nearly coeval with major peaks in Stage 11, Stage 9 and late Stage 7 (Fig. 4b). Large-sized N. pachyderma (s) shows increased abundances during Stage 7, Stage 5, and with one minor spike in Stage 3. At this point it should be stressed that small-sized N. pachyderma (s) records highest test concentrations in Stage 11 (~80,000 tests) with a ratio to N. pachyderma (d) of about 24:1. Within the Eemian and the Holocene this ratio is 6:1 and 4:1, respectively. Obviously, this relation with a continuously decreasing dominance of N. pachyderma (s) over N. pachyderma (d) is caused solely by a reduction in test concentrations of N. pachyderma (s).

Overall, a similar pattern to that in Core M23063 is also recorded in Core PS1243 (Fig. 4e). This applies not only to the ratio of N. pachyderma (s) vs. N. pachyderma (d) in the small-size fraction but also to the major spike in relative abundance of large-sized N. pachyderma (d), which remains restricted to the Eemian time interval in all eastern cores (Fig. 4a-c). Further to the west, in Core PS1244 (Fig. 4d), the ratio between small-sized N. pachyderma (s) and N. pachyderma (d) is about 30:1 during all three major interglacials whereas in Core PS1246 (Fig. 4e) this relation varies between 40:1, 50:1, and 60:1 during the Holocene, Eemian and Stage 11, respectively. In both of these cores from the Iceland Plateau, the prominent spike in relative abundance of large-sized N. pachyderma (d) which is so dominant in the Eemian interval of the eastern cores, has totally vanished. The gradual decrease in predominance of N. pachyderma (s) over N. pachyderma (d) from Stage 11 through the Eemian down to the Holocene also remains in the foraminiferal record of Core PS1906 (Fig. 4f) with ratios of 40:1, 35:1, and 25:1, respectively. Although this site appears to be prone to turbidites which may have led to some size-sorted foraminiferal layers at core depth ~300 and ~415 cm (Hamich, 1991), the records from the Iceland Plateau indicate that the relative abundance of large-sized N. pachyderma (d) shows no major increase during the Eemian interval. Yet, it is noted from the test concentration record in these cores that both large-sized varieties reveal some variability throughout Stages 7-5.

In summary, the following main features are observed:

- In all cores, both small-sized varieties of N. pachyderma are somehow related to each other during the last two interglacials in showing coeval records of test concentrations and relative abundances.
- On a one to one ratio based on interglacial test concentrations, the dominance of N. pachyderma (s) clearly decreases over N. pachyderma (d) from interglacial Stage 11, over Stage 5e, to the Holocene.
- A significant increase in relative abundance of the large-sized variety of N. pachyderma (d) is indicative for the Eemian interval only and is confined to cores from the modern Atlantic Domain.

Subpolar record

As already noted from the faunal distribution pattern in Fig. 3, true subpolar species increase during full interglacial conditions only after glacial conditions have vanished. Among this subpolar assemblage, T. quinqueloba and G. bulloides are the most dominant species due to high test concentrations per sample and/or size fraction. Accordingly, they have a strong interpretative basis and appear to be more suitable as paleoceanographic tools than the other species. Moreover, as will be shown, they also reveal a distinct lateral distribution in the Nordic seas.

The downcore faunal data for T. quinqueloba and G. bulloides are given in Fig. 4a-f alongside those of N. pachyderma. Both species show increased relative and test concentration abundances during interglacial phases. Taking the record from Core M23063 (Fig. 4b) as representative of the eastern Nordic seas, both species display steady increases in test concentrations since Stage 11, with the highest numbers recognized in the Holocene. Beside these records in Stage 11, the Eemian, and the Holocene, increased abundances are also observed during early Stage 7. Towards the west and onto the Iceland Plateau, (i.e. towards decreasing modern surface water temperatures), the distinct downcore pattern from Core M23063 displays some major changes (Fig. 4b-e). The subpolar record of Stage 11 is basically vanished west of Core PS1243. In comparison with Core M23063 the Eemian and Holocene abundance record of G.
is reduced by more than 50% in Core PS1243 and without significance in Core PS1244. If one follows the Eemian and Holocene pattern in each core from the east towards the west, the dominance of the subpolar species in the Holocene over that in the Eemian as revealed by the eastern cores (Fig 4a-c) is already reduced at site PS1244 and eventually is opposite in Core PS1246 (Fig. 4d-e). This is so despite the fact that much lower sample resolution were applied on these Eemian sections than on the Holocene core intervals. In relation to this finding, Core PS1906 with lowest modern surface water temperatures did not yield any subpolar specimens in Stage 11 at all and G. bullioides was encountered neither in the Eemian nor in the Holocene. However, based on the relation of the Eemian and Holocene abundance record of T. quinqueloba together with the oxygen isotope record, Core PS1906 appears to be similar to Core M23063.

In summary, the subpolar record is as follows:

- The stratigraphical occurrence of T. quinqueloba and G. bullioides is mainly tied to the Holocene, the Eemian, and Stage 11 with the least response in the latter interglacial.
- The spatial distribution pattern of G. bullioides is strongly water mass dependent, being confined to the area which is mostly influenced by Atlantic surface water.
- Turborotalita quinqueloba exhibits a wide distributional pattern in the Nordic seas, and is most dominant in the Holocene and Eemian intervals.
- Both G. bullioides and T. quinqueloba are inversely related to N. pachyderma (s) in that their abundances have steadily increased during all three main interglacials since Stage 11, whereas test concentrations of the polar species became reduced during the same time.

A similar change as observed in the faunal pattern of T. quinqueloba is recognized in the oxygen isotopes. Oxygen values of Stage 11 are always slightly higher than Eemian and Holocene values in most cores. Although maybe not very well represented in Cores M17732 and M23063 (the top in Core M17732 is missing and the actual Eemian peak in Core M23063 may not be completely sampled), many isotope records from the Norwegian Sea show similar planktic oxygen values during the Eemian and Holocene (Vogelsang, 1990). Taking this at face value there is a definite change in Core PS1246. Here, oxygen values in the Eemian are about 0.3% lower than in the Holocene.

PALEOCEANOGRAPHIC INTERPRETATION

Stage 11

In terms of terrestrial Pleistocene terminology, Sarnthein et al. (1986) and Shackleton (1987) correlated marine isotope Stage 11 with the Holsteinian warm phase. This is in contrast to studies by Sejrup & Knudsen (1993) who indicate ages which would place the Holsteinian into oxygen Stage 7 rather than into Stage 11. Regardless of this controversy, in Nordic seas sediments only oxygen Stage 11, Stage 5e and the Holocene represent prolonged time intervals which are barren of any IRD (e.g., Birgisdottir, 1990). This inevitably means that ice-berg-melting was low in Stage 11 and hence, the chance that meltwater influenced the water mass circulation in the sense of Broecker & Denton (1989) must have been small also.

The lack of a proper subpolar planktic foraminiferal fauna with 'interglacial-type' abundances (i.e. Eemian or Holocene) is hard to reconcile with the present knowledge of typically glacial and interglacial water mass circulation in the N. Atlantic region. Based on the planktic foraminiferal distribution, it must be assumed (if at all) that the main mass of Atlantic surface water penetrated the Nordic seas as a strong eastern boundary current. Therefore, all cores used in this study would fall within a relatively cold water mass regime with polar imprint. Despite the fact that most areas of the Nordic seas were under strong influence of these polar water masses, a modern-like east to west and southeast to north temperature gradient obviously still existed. A decreasing temperature gradient towards Greenland with 'warm' species in the Norwegian Sea can also be inferred from coccolith studies (Bleil & Gard, 1989; Henrich & Baumann, 1994).

The large easterly expansion of polar surface water masses during Stage 11 may be also reflected in the planktic stable isotope records. Planktic carbon isotope records and their interpretations are much debated, because of a series of complicating factors. These arise from species-dependent 'vital effects' and depth-habitat changes, as well as global sea water $\delta^{13}C$ variations of total CO$_2$ due to gas exchange with the atmosphere in combination with local primary productivity in the surface water (e.g., Berger et al., 1981). However, if it is still assumed that higher planktic carbon isotope values also reflect enhanced surface water ventilation to some degree (Labeyrie & Duplessy, 1985; Vogelsang, 1990), as it is the case with some benthic species (e.g., Cibicidoides wuellerstorfi), then the high carbon values observed in Stage 11 are due to the highest ventilation rate observed in these cores. Interestingly, a close modern analogue to these Stage 11 values is only noticed in Core PS1906. As this site is located near the Polar Front it not only has the lowest summer surface temperatures of all studied sites (Table 1), it is also strongly affected perennially by sea-ice cover (Thiede & Hempel, 1991). Recent data from this area with sea-ice cover
indicate a non-equilibrium state between atmosphere and surface water (Johannessen et al., 1994). Holocene δ18O values of N. pachyderma (s) which would match the values observed in Stage 11 are reported from surface sediments of the ice-covered Arctic Ocean (Spielhagen & Erlenkeuser, 1994). Therefore it appears unlikely that the very high δ18O values in Stage 11 are caused by intense ventilation processes. This assumption is corroborated by a total lack of all epibenthic-living foraminifera, including C. wuellerstorfi, which is rather untypical for interglacials (Belanger & Streeter, 1980; Streeter et al., 1982; Struck, 1992). Instead, the benthic foraminiferal assemblage is entirely composed of endobenthic-living species. Although the actual number of species is relatively high (Struck, this volume), an endobenthic assemblage is more typical for glacial rather than interglacial periods when thermohaline advection was reduced (Struck, 1995). In conclusion, it appears that the Nordic seas were covered by sea-ice most of the year, the summer season was relatively cold but ice-free, thus providing favourable conditions for N. pachyderma (s).

Stage 9-7
The paleoceanographic situation in Stages 9 to 8 was that relatively cold conditions must have prevailed since the planktic foraminiferal assemblage was made up of N. pachyderma only. A similar picture is given by coccolith data which indicate a minor inflow of warmer Atlantic surface water (Bleil & Gard, 1989; Baumann, 1990). Nevertheless, the benthic foraminiferal record for this time period shows high test concentration of C. wuellerstorfi, which indicates good ventilation of the water masses (Vogelsang, 1990; Struck, this volume). In general the situation did not change a great deal during Stage 7, except for the fact that there was an increase in warmer Atlantic surface water which influenced the eastern Nordic seas. This situation led to a slight increase of subpolar abundances at the beginning of Stage 7, whereas the upper part of Stage 7 is dominated by N. pachyderma again.

The general lack of warm water indicating species during Stages 9 and 7 in particular is in contrast to faunal data from the NE Atlantic (−55°N) where both oxygen isotope stages appear as typical interglacials (Ruddiman & McIntyre, 1976; Ruddiman et al., 1986). This would mean that during these times a relatively steep temperature gradient between the Nordic seas and the NE Atlantic must have existed.

Eemian and Holocene
Based on a transfer function to calculate sea surface temperature estimates (SST), Kellogg (1980) reconstructed the paleoceanographic situation for the Eemian and Holocene time interval in great detail and concluded that these periods showed only minor differences. The work by Haake & Pflaumann (1989) essentially came to the same results. They also calculated SSTs which for the northern Norwegian Sea indicate slightly cooler SSTs in the Eemian than in the Holocene. With respect to the present study a simple evaluation of the test concentration record of T. quinqueloba is in absolute agreement with this statement. But in addition, this study has also shown that, if T. quinqueloba is taken as representative for peak interglacial conditions, then the conditions in the Iceland Sea were relatively warmer during the Eemian than during the Holocene. Moreover, this conclusion gains strong support from the oxygen isotope data which also would indicate this relation. Essentially this means that the east to west surface water temperature gradient was less steep in the Eemian compared to the Holocene, but that the southeast to north temperature decrease was maintained, possibly even reinforced.

PLANKTIC FORAMINIFERA AS PALEOCEANOGRAPHIC PROXY
In this study it was clearly indicated that using the same data base, relative and absolute abundances on their own may lead to different interpretations. This is probably best demonstrated using the different varieties of N. pachyderma. It has long been known that different coiling directions in N. pachyderma are somehow related to surface water temperatures (e.g. Ericson, 1959). Furthermore, it has been stated that the left coiling variety (s) makes up more than 95% of the assemblage in waters below −5°C and that this variety has in general a preference for regions with water temperatures below 10°C (Bø & Tolderlund, 1971; Kellogg, 1980). But as yet, it is not known from a biophysiological point of view why even in the Arctic Ocean under most severe polar conditions, N. pachyderma (s) is always accompanied by some percentages of right coiling specimens (Carstens & Wefer, 1992). But despite the well known coiling ratios, N. pachyderma exhibits also a wide range of test morphologies (Kennett, 1968; Keller, 1978; Reynolds & Thunnell, 1986) among which changes in size have been applied as surface water proxy in previous studies (Malmgren & Kennett, 1978).

The cores from the Norwegian Sea have underlined the significance of relative abundances of N. pachyderma (d) for identifying an Atlantic-type water mass during the Eemian and the Holocene. But already in slightly cooler regions of the Nordic seas, relative abundances do not respond positively any more to these peak interglacial conditions. Interestingly, there still is a positive response in the
large-sized variety of *N. pachyderma* (d) but then only in the Eemian interval. This may imply that different test size varieties inhabit different water masses. *Neogloboquadrina pachyderma* (s) is known to show large differences in depth migration during its life cycle, ranging from below 100 m to possibly two hundred meters depth for open water conditions (Hemleben et al., 1989). It, therefore, reflects deeper water below the thermocline rather than the actual surface. But depending on the specific conditions, the upper depth limit in particular may be lower. During ice-covered seasons of the Fram Strait area and the Arctic Ocean, the depth range of *N. pachyderma* sin. seems to be related to a shallower habitat (Carstens & Wefer, 1992).

At those sites with cooler modern temperatures the downcore relative abundance of small-sized *N. pachyderma* (d) varies only on a minor scale almost regardless of glacial or interglacial climatic mode. Therefore, one should refrain from using *N. pachyderma* (d) as a proxy when it makes up less than 15-20% of the assemblage. Overall, the covarying downcore test concentration records of small-sized *N. pachyderma* indicates that the right and left coiling varieties are somehow related to each other, although with notable lags in peak interglacials (Fig. 3, 4a). On the other hand, the fact that ratios of *N. pachyderma* (s) to *N. pachyderma* (d) vary between Stage 11, the Eemian and the Holocene, due to changes in test concentrations of *N. pachyderma* (s) only, may suggest that both forms of the species have different ecological preferences. These may be related to the particular depth habitat and/or by a seasonal off-set in productivity (Reynolds & Thunell, 1986).

Among all subpolar species in the Nordic seas *T. quinqueloba* reflects best interglacial conditions marked by a Holocene-type thermohaline circulation. Furthermore, since this species contains symbionts, its habitat is restricted to the photic zone of the upper surface water, i.e., <100 m (Hemleben et al., 1989). It has been demonstrated in detail that this comparatively small-sized species develops even smaller tests in cooler waters (Bauch, 1992). This is a crucial issue when evaluating the SST estimates based on foraminiferal counts as compiled by CLIMAP workers (1981) since these relied on the >150 μm mesh size. This may be the reason why the inferred relatively warm surface waters in the western Iceland Sea in Eemian times as noted in this study were not recognized previously (Kelllogg, 1980).

When comparing all three major interglacials, Stages 11, 5e, and the Holocene, it is concluded that none of them are alike. Although environmental constraints such as low global ice volume and the lack of drifting icebergs were essentially the same during all of these intervals, the combined investigation of planktic stable isotope and foraminiferal assemblage data reveal major discrepancies in these surface water proxies. They were most likely induced by very different types of Atlantic water mass inflow, which led to the formation of temperature gradients which are not known from the modern Nordic seas. Thus, further detailed studies of the Eemian and Stage 11 should provide more insight into the system of Atlantic thermohaline circulation at high latitudes and help decipher the natural variability of this important climate mechanism.

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