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Benthic foraminifera assemblages in the Central Barents Sea: an evaluation of the effect of combining live and total fauna studies in tracking environmental change

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We present living (stained) benthic foraminifera assemblage data in nine surface sediment samples from the central Barents Sea collected in 2005 and 2006. The abundances of 20 selected species are compared to those from previously published total fauna assemblages of nearby samples. Between 1 and 3 total fauna samples from various years (between 1971 and 1992) are compared with modern (2005 and 2006) samples. The main purpose of the paper is to evaluate the applicability of this comparison. We conclude that, with proper caution, comparing live and total fauna can yield valuable results. Eliminating fragile species, and clustering species according to environmental preferences strengthens the results.
A second purpose of the paper is to assess benthic foraminiferal assemblage change in the basin. The data show that foraminiferal assemblage changes vary strongly through out the basin, with maximum change in the extreme north and south of the study area. Division of the species into three major faunal groups related to specific environmental conditions shows that the abundance of cold water species decreases in the eastern part of the study area, while the abundance of warm water species increases in most of the western area. A reverse trend is seen in the most central locality.

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1. Introduction

The Barents Sea holds major economic resources (oil and gas and fisheries) and as such will most likely be subject to increased human activities in the future. It is a complex and dynamic oceanographic area, exhibiting high seasonal and inter-annual variability, which has large effects on the marine ecosystem and environment (e.g. Furevik, 2001; Dalpadado et al., 2003). There is, therefore, an urgent necessity for knowledge about the present environmental setting compared to past changes in the Barents. On-going monitoring efforts (e.g. Ingvaldsen et al., 2002) extend only a short period back in time, and past variations of the Barents Sea environment are not easy to assess due to a general lack of data. However, one possibility lies in the benthic foraminifera. A voluminous database exists for benthic foraminiferal abundances in the Barents Sea and adjacent shelf areas (Steinsund, 1994; Hald & Steinsund, 1996). This database includes samples going back to the 1960's. These data can be combined with on-going monitoring programs in order to increase our insight into the response of the benthic foraminifera to past changes in natural variability, and long time series reflecting major environmental changes in the region. Only through such investigations using modern

samples together with historical patterns can we begin to distinguish the controlling factors for the observed biological responses to natural and, thereby, longer term environmental changes in the Arctic.

Combining present monitoring with data obtained in the past is, however, not straightforward. There are several reasons for this, including differences in sampling gear and methods in the laboratory, or whether the living, total or dead fauna have been analysed, and different times of the year in which sampling took place. Since the total fauna represents an average over a longer time period this would suggest that comparison with living fauna is unrealistic as previously discussed in numerous papers (e.g. Conradsen, 1993; Murray 2000, Murray, 2006). The extensive data on past foraminiferal assemblages in the Barents Sea is, however, a unique opportunity to investigate more recent changes, if any, in this group of marine species. The main purpose of this paper is to investigate if it is feasible to combine data from the foraminiferal database with data obtained in surface sediment samples from the Barents Sea in 2005 and 2006. For this study we have selected nine new (2005-2006) samples of stained foraminifera, and compared these with 18 nearby total faunal assemblages from the database from the period 1971-1992. We
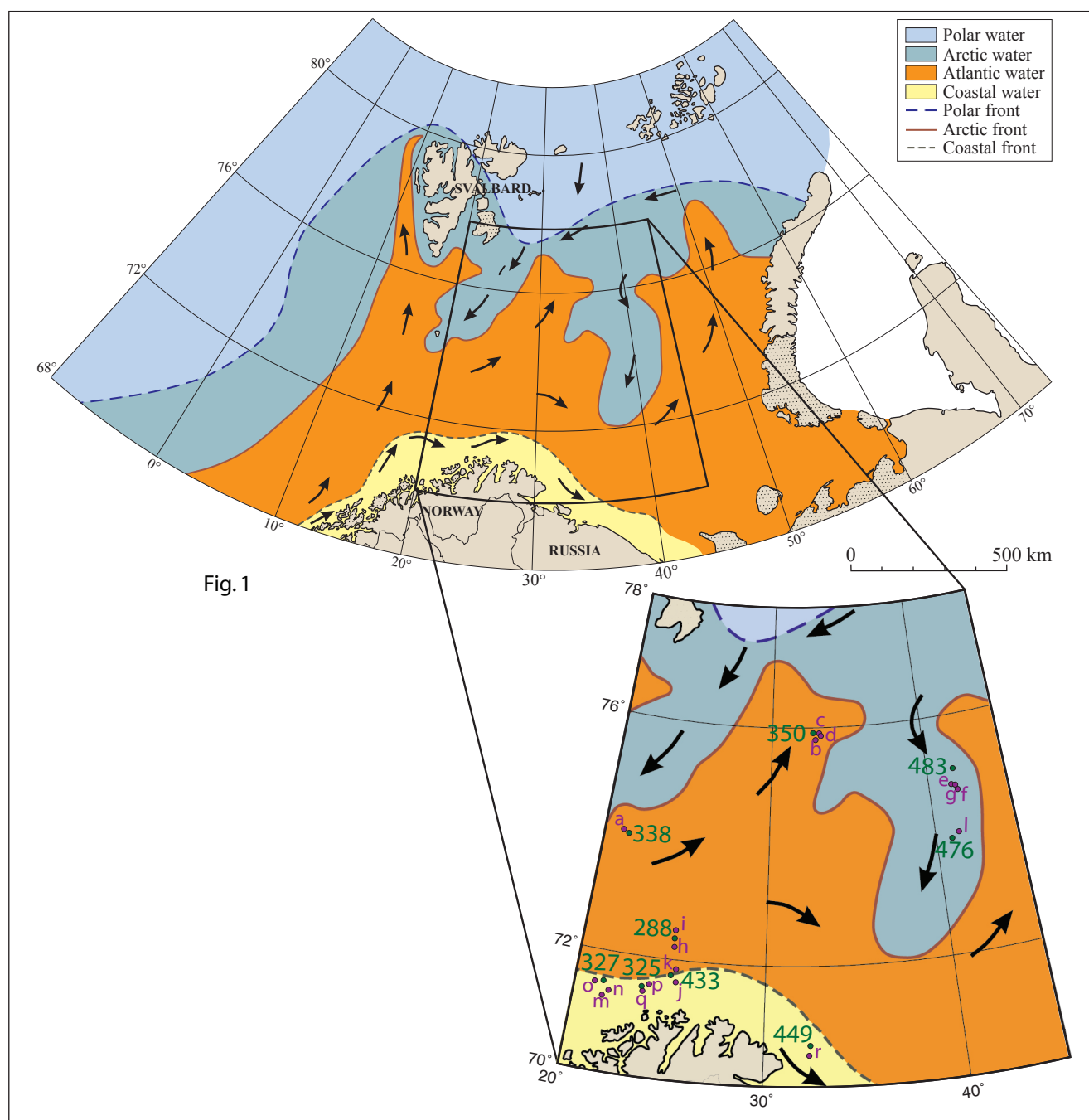
Figure 1. Map of the surface currents in the Barents Sea showing also study area (inset) with location of samples discussed in this study. Green dots: new samples, with sample number given in green. Purple dots: samples taken from the Hald and Steinsund (1992) database, with their sample codes used in this study (purple letters). For more details on samples see Table 1.

evaluate if we can attribute assemblage differences to the different methods used, mainly the difference between total and living fauna.

We further investigate if the limited series of samples from each location, which span several decades, reflect environmental changes, by combining the information documented in the foraminiferal assemblages with climatic data.

Additionally, we will assess if we find any patterns in such environmental changes.

2. Physiographic and oceanographic setting

The Barents Sea is a shallow continental shelf sea, characterized by an alternation of banks (~200 m water depth) and troughs (~400 m water depth). Water masses in the Barents Sea are represented by Atlantic, Polar, coastal, and locally formed waters (Treshnikov, 1985; Carmack, 1990; Loeng, 1991; Hopkins, 1991) (Fig. 1). Warm (>2°C) and high saline (35) Atlantic Water is brought by the Norwegian Current, and continues eastward as the North Cape Current along the northern coast of Norway. The temperature of the surface water

masses may vary seasonally, or due to atmospheric pressure variations by about ± 2°C (Ådlandsvik and Loeng, 1991). The Polar Water is characterized by low temperature and salinity, typically of <0°C and 34.5, and is introduced into the Barents Sea by southwestwards flowing surface currents. The mixture of transformed Atlantic and Polar waters forms the local Barents Sea Water (Hopkins, 1991), typically with temperatures around 0°C and salinities of 34.4-35.

The Norwegian Coastal Current (>2°C) flows along the Norwegian coast above denser Atlantic Water. It is fed by the input from the North and Baltic Sea as well as by local runoff, which helps to maintain its low salinity of <34.7 (Sætre & Ljøen, 1971).

Dense bottom waters are formed during the fall and winter periods from the mixture of transformed Atlantic and Polar waters. Their formation is initiated by cooling of the uppermost water layer, and is completed by removal of brines during the sea ice freezing (Midttun, 1985). The combination of salinity near 35 and temperature close to the freezing point gives these waters extremely high density. The combined influence of brine and Polar Water causes, in general, cool bottom waters in the northern and eastern part of the Barents Sea. The southern and western Barents Sea, south of 74°N and west of ca. 35°E, has higher bottom water temperatures, due to the influence of warm Atlantic Water.

The interaction between the Atlantic and Polar waters produces strong hydrological fronts. The most prominent of these is the Polar front, separating the Polar waters from those brought by the Norwegian Current.

The winter limit of sea ice is mainly controlled by the distribution of upper surface Polar Water (Treshnikov, 1985; Vinje, 1977). In the central part of the Barents Sea, i.e. west of 30°E and south of 74°N sea ice seldom occurs while at 35°E it has its maximum extent as far as 71°N (Shapiro et al., 2006). In the eastern Barents Sea the winter sea ice boundary turns southwards to reach the Russian coast. In summer the sea ice limit typically retreats to the northernmost part of the Barents Sea.

The inflowing Atlantic Water controls the nutrient concentrations in the southern and central Barents Sea (Wassmann et al. 2008). The well-mixed water column resulting from winter convection and the lack of sea ice cover in the central Barents Sea is reflected in the even vertical distribution of high nutrient concentrations observed in March. Primary production increases rapidly in spring (Wassmann et al. 2008).

3. Methods

3.1 The Russian-Norwegian data base

Steinsund (1994) and Hald & Steinsund (1996) presented a large database on calcareous benthic foraminifera from the Barents and Kara Seas (hereafter referred to as the H&S database). This database is based on all available publications at that time, dealing with recent foraminifers from this area. Nearly 600 samples were included in the database (Fig. 2), retrieved from the following sources: Basov and Slobodin (1965), Stoll (1968), Digas (1969, 1971), Slobodin & Tamanova (1972), Østby & Nagy (1982), Stenløkk (1984), Polyak (1985), Khousid (1989), and Hald & Steinsund (1992). Most of the samples were obtained by box-corers and grabs, but 64 samples by Østby & Nagy (1982), and Stenløkk (1984), and 40 Russian samples from the eastern Barents and Kara Seas are core tops. All available information was used to distinguish between modern and relict surface sediments including: the presence of living foraminifers and other organisms, lithology, physical properties, and diagenetic conditions of sediment samples. Even so certain tests re-deposited from relict Pleistocene deposits might be present in some samples. This is especially the case in areas undergoing erosion such as banks or where fish trawling might have taken place. Considering modern sedimentation rates in the Barents Sea, which have been calculated to be on average 0.7 ± 0.4 mm/yr (0.2 – 1.3; Zaborska et al. (2008)), sediment surface samples 1-3 cm thick used in the study could represent periods between 10 and 100 years. Foraminifera were counted in the sediment size-fraction of >0.1 mm. Samples were dried before analysis of the content of living (stained) and dead calcareous foraminifera following the procedure of Meldgaard & Knudsen, (1979).

As the database comprises foraminiferal counts from many scientists, taxonomic discrepancies have been solved by combining certain closely morphologic related species. In particular, the following widely defined species or groups of species were used: (1) *Buccella spp.* including *B. frigida*, *B. tenerrima*, *B. hannai arctica*, (2) *Cibicides lobatulus* including *C. lobatulus*, *C. pseudoungerianus*, *C. refulgens*, *C. rotundatus*, (3) *Elphidium subarcticum* including *E. subarcticum*, *E. frigidum*, *E. magellanicum*, (4) *Islandiella norcrossi* including *I. norcrossi*, *I. helenae*; (5) *Nonionellina labradorica* including *Nonionellina labradorica*, *Nonionella auricula* and (6) *Stainforthia loeblichi* including: *S. loeblichi*, *S. schreibersiana*.

Before performing these modifications a total of 237 species of calcareous benthic foraminifera were registered. After calculating and comparing the mean values, the 20 most frequent species were selected. These twenty species compose an average of 89% of all specimens (total range: 10-100%) in the analyzed samples and their distributions were presented in Steinsund (1994) and Hald & Steinsund (1996). In
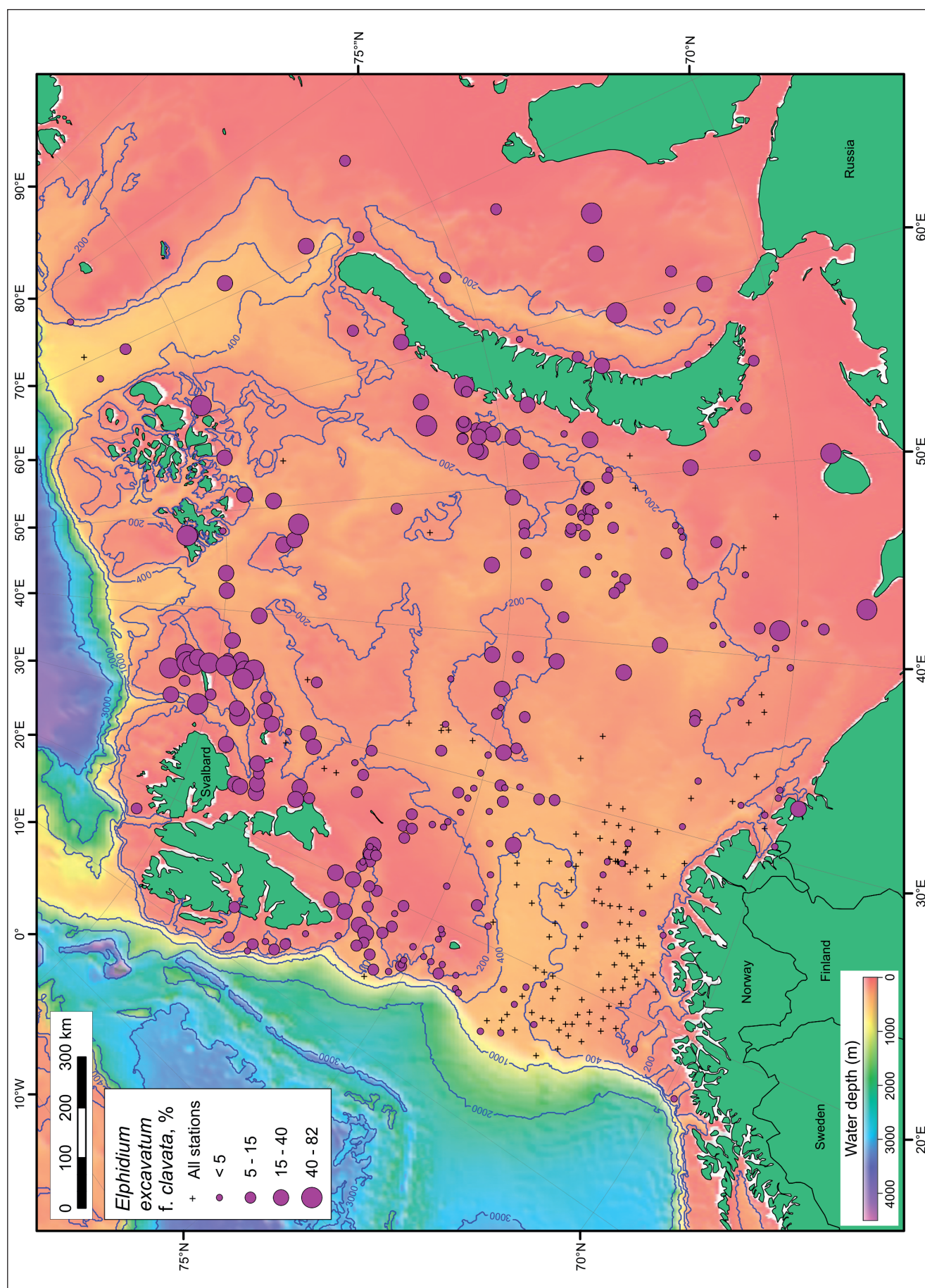
Figure 2. Map indicating the locations of all samples in the Hald and Steinsund database. Abundance data for E. excavatum f. clavata *is incorporated.*

the samples used for this study, there was no reported occurrence of *C. wuellerstorfi*, so this species was left out (Table 1).

The environmental data in the H&S database are average values, based on all available July and August measurements (since 1900) stored at the Norwegian Oceanographic Datacentre, or measurements at sampling stations.

In the H&S database, a slightly different nomenclature was used (*Cassidulina teretis*, *Nonion barleeanum*, and *Nonion labradoricum*). In this study we have updated the taxonomy of the species to include those currently in use (*Cassidulina neoteretis*, *Melonis barleeanum* and *Nonionellina labradorica*).

3.2 New data

The samples were taken during the annually conducted "Ecosystem cruises" in the Barents Sea by the Institute of Marine Research vessel R/V *G.O. Sars*, mainly using a box core, but also by grab sampling. The upper 2 cm ("the fluffy layer") of sea bottom sediments was transferred to a separate vial and stained with a mixture of ethanol and Rose Bengal and kept cool until preparation of the samples in the laboratory.

Samples were wet-sieved in the laboratory using mesh sieves 63-106μm and 106-1000μm. From the 106-1000μm size fraction, around 300 stained (live) specimens were counted in the wet sample including both calcareous and agglutinated species. For this study, only the 20 species documented in the H&S database were considered (Table 1). The total number of specimens of these selected species counted in the samples range between 20 in the east of the study area (sample 476) and 200 in the west (sample 338). The abundances are given as percentages of the total number of specimens of the selected species.

Nine samples from the central Barents Sea have been selected from the new dataset on the basis of proximity to one or more samples from the old dataset of Hald & Steinsund (1996) (Fig. 1). Distances between the new and previously published samples range between 9 and 40 km. Eight of the nine samples from the new dataset have CTD data available on bottom temperature and salinity.

3.3 Rationale for the use of total and live assemblages in combination

In this study we have used a database of total benthic foraminiferal assemblages from a period of several decades as a benchmark for comparison with modern assemblages of live benthic foraminifera in the Barents Sea. This database contains only the 20 most abundant species (or groups of related species) of the total foraminiferal counts. In order to compare our data

with this dataset, we restrict ourselves to these same species. Doing so minimizes two sources of error in such comparisons. The first concerns the overrepresentation of fragile species in the live assemblages, the tests of which are assumed to disintegrate rapidly after their death, thereby introducing a strong secondary faunal difference between live and total fauna. The second error concerns the live fauna which has a stronger seasonal imprint. By only focussing on the species that are abundant in the total fauna the fragile species and those that only thrive in a short period of the year will be eliminated.

We still, however, expect that differences in methodology can affect the comparison of total and live assemblages. In this study we will try to evaluate if this error is small enough compared to the ecological information contained in the two sets of assemblages and which a comparison would reveal. We will first assess the general variability within the total fauna samples and then calculate the difference between the total and live assemblages. We repeat this exercise with the species grouped according to environmental preferences in order to improve the signal to noise ratio. As a sensitivity test, we also perform these calculations after transforming the data in such way that the rare species are emphasised. If the difference between the total and live assemblages is of the same order of magnitude as between the total assemblages, and there is agreement between the differences in fauna and environment, then the error due to method difference is acceptably small.

3.4 Evaluation of taxonomic species groups

In order to achieve maximum comparability, we present our results according to the same taxonomic divisions as Hald and Steinsund (1996), which include the lumping together of several morphologically related species. While possibly minimising artefacts due to taxonomic confusion, this procedure does introduce another possible source of error. In order to have a feasible chance to compare total fauna counts with live fauna counts, we need to concentrate on only robust species, as the fragile tests will be underrepresented in the fossil assemblage. This was automatically achieved as the H&S database only gives the abundances of the 20 most common species. However, as some species were first lumped into taxonomic groups, only after which these 20 most common species were selected, fragile species that were lumped with highly abundant robust species could, in that way, end up in the database.

In the H&S database the species *Nonionella auricula* was lumped with *N. labradorica* for morphological reasons. However, this fragile species challenges the comparability of the total with the live assemblages. Furthermore, in the Barents Sea, these two species have profoundly different environmental preferences. As *N. auricula* is highly abundant in the new recent samples

Table 1. Foraminifera species abundances for all new samples presented in this study and discussed in the

Abundances of only 19 of the 20 species used in the H&S database are given as none of the samples discussed in this study contains specimens of C. wuellerstorfi. *Abundances of* N. labradorica *are given in addition to those of* N. labradorica *lumped together with* N. auricula. *The sample codes correspond to those in Fig. 1. Abundances are given as percentages of these selected 20 species, and thus add up to 100%. The total number of counted foraminifera is given (tot #),*

Sample code	Sample name	*Astrononion gallowayi*	*Buccella spp.*	*Cassidulina laevigata*	*Cassidulina obtusa*	*Cassidulina reniforme*	*Cassidulina neoteretis*	*Cibicides lobatulus*	*Discorbinella spp.*	*Elphidium excavatum f. clavata*	*Elphidium subarcticum*	*Epistominella nipponica*	*Islandiella islandica*	*Islandiella norcrossi*	*Melonis barleeanum*	*Nonionella labradorica/Nonionella auricula*	*Nonionellina labradorica*	*Pullenia bulloides*	*Stainforthia loeblichi*	*Trifarina angulosa*	*Trifarina fluens*	BCI (20 on species, raw)	BCI (on 20 species, transformed)	BCI (on 20 species excl. N. auricula, raw)	BCI (on 20 species excl. N. auricula, transformed)
		T	C	W	T	C	C	T	T	C	C	W	C	C	W	C	C	T	C	T	T				
476	GOS 476	0,0	30,0	0,0	0,0	15,0	0,0	25,0	0,0	15,0	0,0	0,0	0,0	5,0	0,0	0,0	0,0	0,0	5,0	0,0	5,0				
l	71di0392	1,7	45,0	0,0	0,0	0,0	0,0	11,7	0,0	18,3	13,3	0,0	0,0	1,7	1,7	6,7	6,7	0,0	0,0	0,0	0,0	0,42	0,43	0,42	0,45
483	GOS 483	10,0	23,3	0,0	0,0	0,0	0,0	10,0	0,0	16,7	0,0	0,0	0,0	10,0	0,0	10,0	3,6	0,0	10,0	0,0	10,0				
g	92-Pol-123	0,0	50,0	0,0	0,0	0,0	0,0	14,3	0,0	7,1	0,0	0,0	0,0	14,3	0,0	7,1	7,1	0,0	0,0	0,0	7,1	0,35	0,19	0,35	0,20
f	88ba0072	8,7	30,4	0,0	0,0	8,7	0,0	13,0	0,0	8,7	21,7	0,0	0,0	8,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,41	0,39	0,41	0,39
e	71di0393	0,0	27,6	0,0	0,0	0,0	0,0	0,0	0,0	48,3	3,4	0,0	0,0	10,3	0,0	10,3	10,3	0,0	0,0	0,0	0,0	0,52	0,39	0,54	0,40
350	GOS 350	4,8	6,0	0,0	0,0	8,4	0,0	4,8	0,0	0,0	0,0	2,4	0,0	16,9	48,2	1,2	1,2	0,0	2,4	0,0	4,8				
d	T-92-20-00	7,1	10,5	0,0	0,0	0,4	8,8	49,9	0,0	0,8	0,7	2,2	0,8	7,0	0,4	4,6	4,6	0,0	0,4	0,0	6,3	0,66	0,29	0,67	0,29
c	71di0377	1,1	30,3	0,0	0,0	0,0	0,0	3,4	0,0	0,0	0,6	0,0	5,6	6,7	23,0	12,9	12,9	0,0	2,2	0,0	14,0	0,66	0,31	0,70	0,32
b	71di0380	2,0	14,5	0,0	0,0	19,8	0,0	1,1	0,0	0,0	9,4	0,3	0,2	23,9	3,1	8,5	8,3	0,8	6,2	0,0	10,3	0,51	0,25	0,54	0,26
449	GOS 449	0,7	0,0	3,0	0,0	5,9	3,0	0,0	0,0	0,0	0,0	12,6	0,0	1,5	63,7	5,9	0,0	3,0	0,7	0,0	0,0				
r	92-Pol-047	5,4	4,5	0,0	0,4	24,4	26,4	6,2	0,0	0,4	0,8	0,0	0,0	0,0	20,7	2,1	1,7	3,3	0,4	0,0	5,0	0,64	0,44	0,66	0,51
338	GOS 338	0,0	7,0	0,5	0,0	12,5	13,5	9,5	0,0	0,0	0,0	12,5	0,0	17,5	10,5	2,0	0,0	3,0	0,0	2,5	9,0				
a	82on0004	7,5	10,2	0,0	0,0	6,5	2,2	10,8	0,0	0,5	8,6	0,5	0,5	11,3	14,0	7,0	6,5	1,1	0,5	0,5	18,3	0,40	0,26	0,42	0,31
288	GOS 288	0,0	0,0	0,0	0,0	0,9	7,8	25,9	0,0	0,0	0,0	31,9	0,0	0,0	17,2	9,5	0,0	0,9	0,0	6,0	0,0				
i	90-T-05/1	2,7	0,0	7,3	0,0	2,6	0,0	18,8	0,0	0,0	0,8	7,3	0,0	52,1	0,0	0,0	0,0	3,8	0,6	0,0	4,1	0,55	0,48	0,53	0,43
h	84-T-32/3	0,0	0,4	0,0	0,0	0,0	0,0	10,4	1,3	0,0	0,0	24,3	0,0	61,3	0,0	0,0	0,0	1,3	0,0	0,9	0,0	0,29	0,43	0,29	0,45
433	GOS 433	0,7	0,0	3,7	0,0	0,0	9,6	9,6	0,0	0,0	0,0	23,0	0,0	0,0	29,6	14,8	0,0	0,7	0,7	7,4	0,0				
k	84-T-34/1	1,7	5,4	0,8	0,4	1,2	4,1	17,8	2,1	0,0	0,0	32,6	0,0	0,0	30,2	0,0	0,0	1,7	0,4	1,7	0,0	0,29	0,27	0,23	0,22
j	84-T-35/3	2,1	0,0	2,1	4,6	0,4	9,6	34,5	5,7	0,4	0,0	15,3	0,7	0,0	6,4	0,0	0,0	1,4	0,0	16,7	0,0	0,47	0,22	0,48	0,23
327	GOS 327	0,0	0,0	3,0	0,0	0,0	6,7	3,0	0,0	0,0	0,0	45,2	0,0	3,0	2,2	18,5	0,0	8,9	0,7	8,9	0,0				
o	85-T-13/1	0,4	0,0	11,2	0,7	0,0	4,7	16,9	4,0	0,0	0,0	46,0	0,0	0,0	3,6	0,0	0,0	3,6	0,0	9,0	0,0	0,30	0,30	0,27	0,25
n	84-T-9/1	0,0	0,0	0,5	0,5	0,0	4,9	22,4	4,4	0,0	0,0	57,1	0,0	0,0	2,9	0,0	0,0	1,5	0,0	5,9	0,0	0,17	0,09	0,17	0,09
m	83-T-26/2	0,0	1,2	2,3	0,0	0,0	6,2	17,4	23,2	0,0	0,0	35,5	0,0	0,0	0,4	0,8	0,0	2,3	0,0	10,8	0,0	0,30	0,19	0,29	0,16
325	GOS 325	0,0	0,0	0,0	0,0	0,0	11,5	13,5	0,0	0,0	0,0	35,4	0,0	1,0	2,1	20,8	0,0	9,4	0,0	6,3	0,0				
q	85-T-40/1	3,6	1,6	2,3	3,6	0,0	3,6	11,8	4,6	0,0	0,0	32,9	0,7	0,0	2,0	0,0	0,0	0,0	0,0	32,2	0,0	0,42	0,40	0,41	0,37
p	84-T-4/1	0,5	0,5	0,5	1,4	0,0	1,4	10,3	1,9	0,0	0,0	47,7	0,0	0,0	9,8	0,0	0,0	1,9	0,0	24,3	0,0	0,23	0,13	0,23	0,13

(up to >20%), the lumping of these species obscures the faunal signal. In the modern samples, the morphological distinction is indisputable, and we therefore present not only our results in accordance with the H&S taxonomy, but also with *N. auricula* removed. As a

check on whether this pattern is consistent, we looked at the abundances of the other species of *Nonionella* in all samples: *N. iridea*, *N. turgida*, *N. turgida digitata* and one not further identified *Nonionella sp.*. All are almost absent in the total assemblages, and highly abundant

H&S database samples.

as well as the total number of specimens belonging to the selected 20 species (tot # 20 species). Species groups indicated: W – warm water species, C – cold water species, and T – temperature tolerant species. Sample coordinates, water depth, and environmental parameters are indicated. Both temperatures and salinities from the H&S database and Conkright et al. (2001) are given. The Bray-Curtis Index of dissimilarity (BCI) is given for the sample pairs (value refers to the difference between the sample in the row above the given value and the row in which the given value is placed).

% warm water species	% cold water species	% temperature insensitive species	% warm water species (excl. N. auricula)	% cold water species (excl. N. auricula)	% temperature insensitive species (excl. N. auricula)	tot # 20 species	tot #	% 20 species	BCI (on 3 species groups, raw)	BCI (on 3 species groups, transformed)	BCI (on 3 species groups excl. N. auricula, raw)	BCI (on 3 species groups excl. N. auricula, transformed)	Longitude (°E)	Latitude (°N)	Water depth (m)	Year	date	Temperature (°C) (GOS: CTD; H&S: from H&S database)	Salinity (GOS: CTD; H&S: from H&S database)	Temperature (°C) (GOS: CTD; H&S: from Conkright database)	Salinity (GOS: CTD; H&S: from Conkright database)	Temperature (°C) (GOS: CTD; H&S: from Conkright database, av.)	Salinity (GOS: CTD; H&S: from Conkright database, av.)	Distance (km)
0	70	30	0	70	30	20	322	6					40,951	73,960	245	2005	2-9-	-0,4	34,9	-0,4	34,9	-0,4	34,95	
2	85	13	2	85	13	60	2785	2	0,17	0,07	0,17	0,07	41,417	74,050	227	1971		-0,3	34,0	-0,6	34,9	-0,6	34,90	17
0	70	30	0	68	32	30	334	9					41,669	75,109	174	2005	4-9-	-0,3	35,0					
0	79	21	0	79	21	14	272	5	0,13	0,13	0,11	0,12	41,667	74,833	180	1992		0,0	0,0					31
0	78	22	0	78	22	23	244	9	0,05	0,07	0,00	0,07	41,750	74,750	190	1988		0,0	33,8					40
0	100	0	0	100	0	29	420	7	0,22	0,17	0,22	0,17	41,417	74,850	180	1971		0,1	33,8					30
51	35	14	51	35	14	83	352	24					32,693	75,905	318	2006	30-8-	1,2	35,1	1,2	35,1	1,2	35,05	
3	34	63	3	34	63	759	1736	44	0,49	0,19	0,49	0,19	33,217	75,850	171	1992		0,0	0,0	0,9	34,9	0,7	34,93	15
23	58	19	23	58	19	178	479	37	0,45	0,09	0,45	0,09	32,833	75,783	225	1971		0,5	33,8	0,8	34,9	0,7	34,93	14
3	82	14	3	82	14	648	998	65	0,24	0,09	0,24	0,09	33,100	75,900	260	1971		0,5	33,8	0,5	34,9	0,7	34,93	11
79	17	4	84	12	4	135	326	41					32,311	70,685	278	2005	25-8-	2,6	34,7	2,6	34,7	2,6	34,75	
21	59	20	21	59	20	242	513	47	0,56	0,35	0,64	0,41	32,233	70,517	258	1992		4,2	35,3	3,2	34,9	3,2	34,89	19
24	53	24	24	52	24	200	328	61					21,483	74,000	299	2006	25-8-	2,8	35,1	2,8	35,1	2,8	35,08	
15	47	38	15	47	38	186	193	96	0,14	0,16	0,14	0,19	21,132	74,048	310	1982		1,0	34,6	2,6	35,0	2,6	35,04	12
49	18	33	54	10	36	116	324	36					24,940	72,362	261	2006	22-8-							
67	4	29	67	4	29	1084	1728	63	0,18	0,15	0,12	0,11	24,940	72,500	246	1990		5,5	34,9	4,1	35,0	4,1	35,04	15
86	0	14	86	0	14	230	305	75	0,19	0,17	0,19	0,17	24,983	72,216	270	1984		4,0	35,0	4,1	35,0	4,1	35,04	16
56	25	19	66	12	22	135	305	44					24,937	71,743	267	2005	19-8-	5,0	35,1	5,0	35,1	5,0	35,11	
64	11	25	64	11	25	242	315	77	0,14	0,08	0,03	0,14	25,195	71,850	277	1984		4,2	35,0	4,3	35,0	4,7	35,04	15
24	11	65	24	11	65	281	301	93	0,40	0,10	0,40	0,10	25,236	71,634	220	1984		4,3	35,0	5,0	35,0	4,7	35,04	16
50	29	21	62	13	25	135	313	43					21,500	71,502	339	2006	21-8-	5,0	35,1	5,0	35,1	5,0	35,13	
61	5	35	61	5	35	278	313	89	0,24	0,27	0,09	0,21	21,037	71,475	325	1985		4,5	35,0	4,5	35,1	4,6	35,07	17
60	5	35	60	5	35	205	315	65	0,00	0,07	0,00	0,07	21,833	71,360	327	1984		4,5	35,0	4,5	35,1	4,6	35,07	20
38	8	54	39	7	54	259	306	85	0,22	0,09	0,22	0,06	21,533	71,257	297	1983		4,5	35,0	4,8	35,1	4,6	35,07	27
38	33	29	47	16	37	96	323	30					23,502	71,502	361	2006	19-8-	5,3	35,1	5,3	35,1	5,3	35,14	
37	6	57	37	6	57	304	363	84	0,28	0,22	0,20	0,17	23,867	71,552	338	1985		4,3	35,0	4,1	35,1	3,9	35,05	14
58	2	40	58	2	40	214	329	65	0,21	0,09	0,21	0,09	23,572	71,425	364	1984		4,5	35,0	3,8	35,1	3,9	35,05	9

in the live assemblages, indicating that this is probably a secondary signal and not the result of environmental changes.

In order to demonstrate the influence of this species on the analyses performed in this study, the results achieved both using and excluding *N. auricula* are presented. Showing both sets of results will possibly provide other users of the H&S database with an estimate of the influence of this species.

3.5 Quantification of differences between samples

The differences between the foraminiferal assemblages are quantified using the Bray-Curtis Index of dissimilarity (Eq. 1; BCI; Bray & Curtis, 1957). We chose this index, because it compares each foraminiferal species from one sample to the next (paired method), instead of considering all species at the same time. Moreover, the method can be used on datasets containing zeroes. For these reasons BCI is to be preferred over e.g. the Student's t test, Chi squared, and the Kolmogorov-Smirnov test. The first only detects significant differences in mean, the second can only be applied to frequency data, and the third method is not a paired calculation.

In order to make the samples comparable, all foraminifera counts and percentages were recalculated to percentages adding up to 100%. We performed these calculations on the sample pairs in each locality that are adjacent in time, as follows:

$$BCI_{jk} = \frac{\sum_{i=1}^{s} \left| Y_{ij} - Y_{ik} \right|}{\sum_{i=1}^{s} \left(Y_{ij} + Y_{ik} \right)}$$

Eq. 1

where BCI_{jk} is the Bray-Curtis index of dissimilarity between sample *j* and sample *k*, Y_{ij} is the abundance of the *i*th species in the *j*th sample, and Y_{ik} is the abundance of the *i*th species in the *k*th sample. The values of the BCI of dissimilarity range from 0 (identical samples) to 1 (entirely different samples).

These calculations are repeated after transforming the data by taking the fourth root of the percentages (M. Greenacre, pers. comm.), in order to reduce the emphasis on the more abundant species. This means we assign more weight to the appearance and disappearance of species that are rare, and are therefore possibly nearer the boundary of the environment where they thrive, than to fluctuations within species that are abundant. The results of the calculations can be found in Table 1.

4. Results and discussion

The foraminiferal counts, of both the samples from the H&S database and the new data, are listed in Table 1. Listed are also the environmental data and the BCI values.

4.1 Faunal distribution pattern in the study area

Table 1 gives some insight into the variability in foraminiferal assemblages between locations in the region over time. Overall, the samples show two main groups based on the content of some characteristic species. There is a northern sample group (338, 350, 483, 476) based on their similarity in containing *I. norcrossi* and *Buccella spp.* in all samples and during the entire time period studied. In the two most north-easterly samples (483 and 476) *E. excavatum* occurs. The southern samples (327, 325, 288, 433, 449) are, in contrast to the northern samples, characterised by high occurrences of *M. barleeanum* along with high abundances of *E. nipponica*. Moreover, *T. angulosa* is present in all samples except the most eastern sample, 449, where *T. fluens* is found. This overall distribution pattern is generally similar to previous findings by Hald & Steinsund (1996). A more detailed comparison is in preparation.

By using former knowledge of ecologic preferences (Knudsen, 1992 and Seidenkrantz and Knudsen, 1997) of the relevant species three major environmental faunal groups termed, 'warm water species', 'cold water species' and 'tolerant species' were erected (Table 1). These clearly portray the southern and the northern sample groups, and the environmental gradient existing between them (Fig. 3).
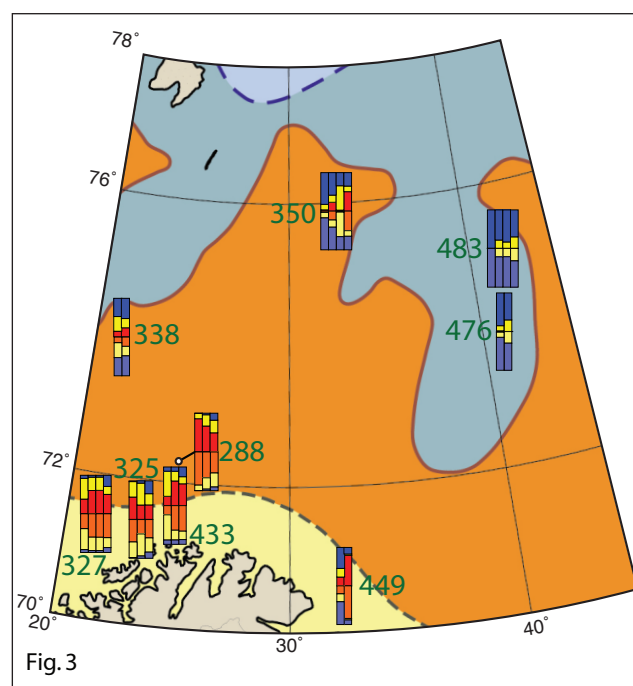

Fig. 3

Figure 3. Percentages of the three temperature related groups of foraminifera species: warm water species (red), temperature tolerant species (yellow) and cold water species (blue), at each sample locality. The centre of each bar diagram is placed at the location of the sample of which the code number is given next to the bar diagram. Note that due to lack of space, the bar diagrams of locality 288 have been offset; original location indicated by circle. The percentages are calculated based on the original data; i.e including N. auricula. *In mirror image, and in subdued colours, the calculated results are given excluding* N. auricula *are given. The bar diagrams give the data in chronological order, from left to right. Values can be found in Table 1.*

4.2 BCI variability within localities

The differences between each of the temporal samples in the H&S database from the various localities, quantified by means of the Bray-Curtis Index of dissimilarity (BCI), provide insight into the variability in the foraminiferal assemblages. The BCI values are presented in Table 1 and Fig. 4. In the text, we present the values in couples, i.e. calculated with *N. auricula*/calculated without *N. auricula*. First we examine BCI values of sample pairs from the H&S database. These range from 0.17/0.17 to 0.66/0.70, with an average of 0.35/0.37 and a standard deviation of 0.19/0.21. The highest values are found in sample localities 350, mainly due to a shift from *Buccella spp.* and *M. barleeanum* to *C. lobatulus*, and the lowest in south-western localities 327 and 325.

The BCI values of the pairs of samples with one from the H&S database and one new sample vary between 0.29/0.23 and 0.66/0.67, with an average of 0.40/0.40 and a standard deviation of 0.19/0.20 (Table 1). The samples which show the highest BCI between the H&S database and the new data are 350, where *C. lobatulus* diminishes again in favour of *M. barleeanum*, and 449, where *C. neoteretis* almost vanishes while *M. barleeanum* thrives (table 1). The lowest values are found in sample localities in the southwest: 327 and 433.

The population of BCI values for adjacent samples from either the H&S database, or from the H&S database and the live assemblage counts, is not statistically different. This implies that the method difference is so small that it cannot be detected in the BCI values calculated on

the basis of 20 species. Furthermore, the spatial pattern in the BCI values is comparable with high values in localities at 350 and low values in the southwest.

Taking all BCI values within the sample localities together results in a pattern, with the highest differences in the eastern and north-western part of the basin (449, 350, 483, 476, and 338), and lowest level of change in the southwest (288, 433, 325, 327) (Fig. 4).

4.3 Changes in environmental faunal groups through time

The homogeneous variability, as expressed by BCI values in all our samples, suggests the time period represented by the total fauna assemblages is small with respect to the temporal sample spacing. This allows us to evaluate the faunal changes through time as documented in the samples. In order to facilitate the detection of trends in time we plotted the ratios of the three major foraminiferal faunal groups in all samples (Fig. 3.) The results are given both with (bright colours) and without (subdued colours) *N. auricula*. From this plot it becomes apparent that, in both scenarios, the changes in the ratios of these three environmental groups are highly variable. The warm water group occurs with high abundances in the southern part of the central Barents Sea. Through time it consistently increases in abundance at two localities (338, and 449), while it decreases at 288, and varies at 350. At localities 327, 325 and 433 the trend depends on which scenario is chosen; with the possibly disturbing presence of *N. auricula*, 325 and 433 show an
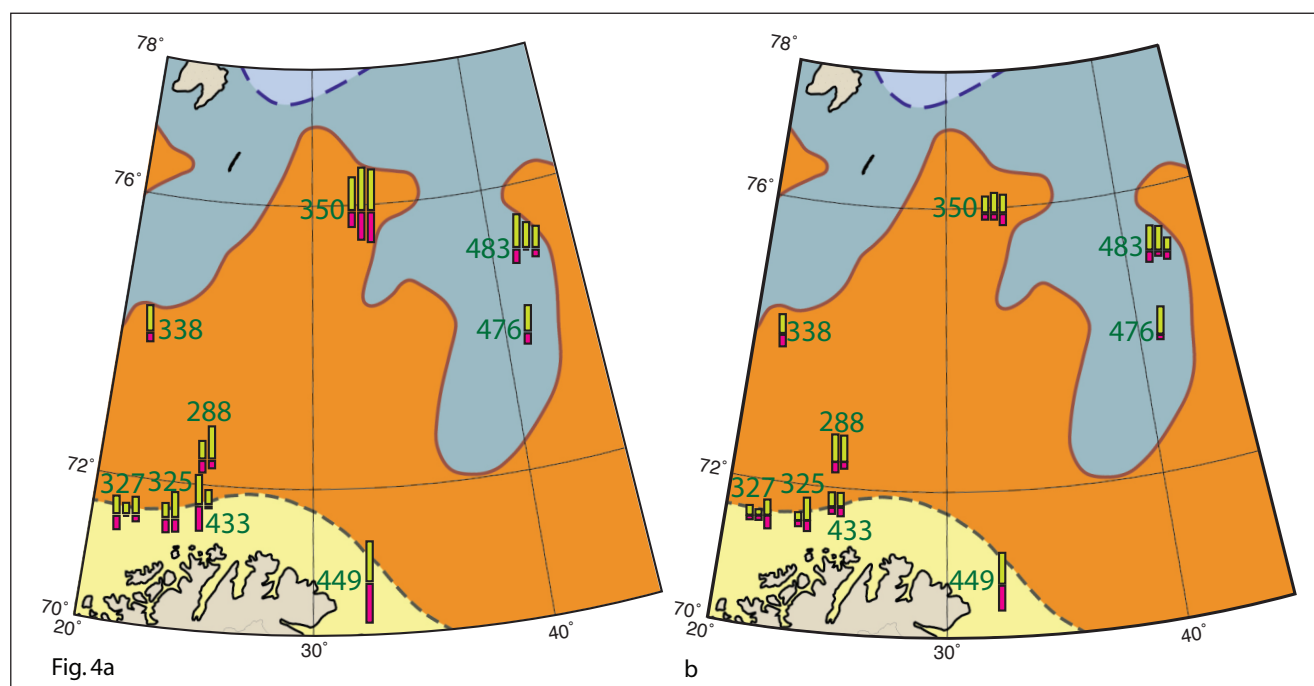

Figure 4. BCI values of all chronologically adjacent sets of samples within each sample locality, given in chronological order, from left to right. Fig. 4a: raw data; Fig. 4b: transformed data (fourth root of percentages). In green: BCI values calculated on all 20 species. In pink: BCI values calculated for three species groups. In order to enhance readability, only the values excluding N. auricula *are given. Values can be found in Table 1.*

irregular pattern while 325 shows a decrease. With this species eliminated, 327 and 433 show a steady increase in the warm water group while 325 shows an irregular pattern.

At the same time, several of the southern localities (288, 327, 325, 433) show a considerable increase in the abundance of the cold water group (up to >30%) (Fig. 3). This is, for a large part, due to high abundances of *N. auricula*. The bar charts without this species show either a diminished (327, 325, 288) or negligible (433) increase in cold water species. Without *N. auricula*, the southern samples (325, 327, 288, 449) do not have higher percentages of cold water species than 13%, almost entirely due to *C. neoteretis*; these values are of similar magnitude as in the older samples. The cold water group shows decreases in abundance at localities 350, 483 and 476, samples of which are located in the northeastern part of the study area, close to the Polar front. The strongest assemblage change is found in the extreme southeastern part of the study area (locality 449) where the cold and temperature insensitive groups decrease strongly along with an increase in the warm water group. This faunal change is mainly caused by *M. barleeanum* and *E. nipponica* (warm water group) and a decrease of *C. reniforme* (cold water group). Altogether, in the northwestern and southern parts of the studied basin, the abundance of warm water species is increasing. The abundance of cold water species is weakly increasing in the south-west, due to an increase in *C. neoteretis*, and considerably decreasing in the east of the study area, mainly due to a reduction in *Buccella spp.* and *N. labradorica*. In the abundance changes of the temperature tolerant species, a weak decrease can be seen in the SW part of the basin (mainly due to *A. gallowayi*, *C. obtusa* and *Discorbinella sp.*), while a weak increase is visible in the mid-east of the study area (mainly due to an increase in *C. lobatulus*).

When evaluating the trends within these localities, one should be aware of the differences in time coverage between the localities (from 13 years at 449 to 35 years at 350), and the time between the specific samples (from 0 at 350 and 433, to 34 at 476). In general, the changes seen in each locality appear more gradual than abrupt, possibly indicating roughly comparable rates of environmental change over the period studied.

4.4 Variability of BCI calculated from environmental groups within localities

When quantifying the differences between the samples through calculating the BCI on all pairs of species percentages, our results may be obscured by the equal weight attributed to changes from one species to another if they have comparable environmental preferences. For instance, a reduction in *I. islandica* combined with an increase in *I. norcrossi*, all with an affinity to cold water masses, has the same effect on the BCI

calculated on the 20 selected species, as a reduction in *I. islandica* combined with an increase in *C. laevigata*. This is despite the latter change being much more environmentally significant, due to strong differences in ecologic preferences of these two species. In order to obtain a firmer grasp on the faunal data, we have also calculated the BCI for all pairs of samples based on the differences in abundance of environmental groups (cold water fauna, warm water fauna, tolerant fauna; Fig. 3). The observed differences between the samples agree better with the environmental information as contained in the foraminiferal assemblages; e.g. the high BCI value of locality 449 (Table 1), which is largely caused by a reduction in *C. reniforme* and *C. neoteretis* (cold water species), and an increase in *M. barleeanum* (warm water species). The latter is still high after lumping the species into groups (Fig. 4a). The high BCI value based on the 20 species in sample 476 (Fig. 4a) is largely based on the exchange of the cold water species *E. subarcticum* and *N. labradorica* for cold water species *C. neoteretis* and *S. loeblichi*, and is subsequently reduced when the value is calculated for the environmental groups (Table 1). This transformation fits well with the small change in temperature and salinity. The pronounced change toward warmer species from 1992 to 2006 at locality 350, synchronous with a 0.5°C temperature increase, is also expressed better in the BCI calculated for environmental groups. The highest BCI value being found at locality 449, and the lowest at 327, is the same as seen in the ungrouped data (Fig. 4a). The overall pattern of low values in the southwest and higher values elsewhere, however, is not apparent. This phenomenon may be explained by the harsh conditions prevailing in the northeastern part of the study area, and the consequent low abundances of calcareous species. The high variability in the 20 species at localities 483 and 476 can be an artifact due to the small number of specimens on which the percentages are calculated. With the species lumped into three groups this effect is diminished.

4.5 BCI variability on transformed data

When calculating BCI values on sample sets, the results are dominated by the abundant species. Their high abundance may indicate that the environmental parameters at the sample location are near the optimum for these species. A small environmental change would therefore only have a modest effect on their abundances. The rare species, however, may experience an environment close to their tolerance limits in the same samples, and therefore be more sensitive to environmental change.

Furthermore, the BCI values of the untransformed data show that variability within the H&S database and between the H&S database and new samples is of the same magnitude. Calculating BCI values on transformed data would determine if the less abundant species are equally comparable in both data sets. Such

low abundances may possibly have a secondary cause, namely dissolution within the total fauna, the effect being minimized by the selection of the species, but not entirely eliminated. The same holds for species with their abundance peaks at the time of sampling of the new samples. We therefore repeat our calculations after transforming the percentage data by taking the fourth root, thereby assigning greater relative weight to the rare species.

The results (Table 1, Fig. 4b) show that the BCI values of the transformed data indeed differ significantly between intra- and extra-H&S database samples. The average BCI value for the last time step (H&S database to new sample) for the grouped and transformed data is ~75% higher than the average BCI value for such data calculated on steps from one H&S sample to another. This could either mean the two sample sets are not comparable when it comes to rare species, or the rare species reveal increased environmental change in the time step between the H&S database and the new samples.

4.6 Relating faunal variation and environment

When assessing the possible relationship between the faunal and environmental data here presented, we have to take into account that both our environmental and our faunal data have several, and quite different, sources, and together represent four different time scales. As for the faunal data, the changes within the H&S database, and between the database and the new samples, do not reflect year-to-year environmental changes. As mentioned earlier, the assemblages of the samples in the H&S database form a mixture of live (recent) foraminifera and up to a 100 years' content of fossil foraminifera, of which the ratio is unknown. These therefore reflect some weighted averages of environmental parameters over, most likely, several decennia, but with emphasis on the last year. The concomitant environmental data represent either a moment (CTD) or the average summer temperatures over almost a century (NOD data). Unfortunately, the H&S database does not disclose which samples come with what type of data. In order to work with consistent data, at least within the database, it can be advisable to extract environmental information from another source, such as Conkright et al. (2001). Parameters for all H&S sample locations were extracted from this atlas by Sergei Pisarev (unpublished data), and from this selection, we took annual average bottom water temperatures (Table 1).

The newly presented faunal data most likely represent a several month period, while the concomitant environmental data are all CTD measurements, representing only minutes. As it is practically impossible to acquire temperature data that represent the same time period as the faunal assemblages, it is approximations

which offer the best solutions. The Conkright data represent an average over a longer time than the coverage of the database, so the only differences between them represent spatial variability. As we treat the various samples from one sample locality as spatially indistinguishable, we chose to average the temperature and salinity data for the H&S database samples within this one locality. This also avoids the false suggestion that the values give information on changes through time. This means we cannot relate the faunal changes within the H&S samples to environmental changes, and have to limit ourselves to comparing the H&S database with the modern samples. We can then compare these background values with the modern CTD values. This difference between the 2005/06 values and the long term average is an indication of recent change, just as the difference between the total fauna counts and the modern, live assemblages may be.

All samples for which we have environmental data, except for 449, show an increase in both temperature and salinity (Table 1). Locality 449 shows an opposite trend. This means the northern sample localities (350, 483 and 476) with their decrease in cold water species show congruent trends in environment and fauna. The south-western samples (327, 325, 433) show a slightly less unambiguous relation; the temperature increase comes together with an increase in warm species in only two of these three samples, while the abundance of the cold water species increases in all three. The locality with the highest BCI value, namely 449, has opposite faunal and environmental trends. While the fauna shows the most conspicuous increase in warm water species and decrease in cold water species, the environmental data show a pronounced cooling and freshening. Possibly, the high variability at locality 350 is related to movement of the polar front. The high variability at location 449 may be a result of variations in properties (amount, temperature, salinity) of the inflowing Atlantic Water, related to the distance of the location (449) to its source. Altogether the data suggest a fairly good correspondence between relative faunal change and environmental parameters as expressed by our temperature and salinity data. The correspondence is weakest at the highest faunal variability. This may be explained by the environment in such locations being so highly variable that either the fauna is not able to keep up, and is out of equilibrium with it, or perhaps the CTD measurements are not representative in such strongly changing areas.

The relation between BCI value and magnitude of deduced environmental change is less straightforward. There is a positive correlation between absolute temperature change and BCI (only those between the H&S database and the new samples), but this correlation is weak both for the raw and transformed data.

In general, a mismatch between faunal assemblages and temperature/salinity data can be explained if

the foraminifera are influenced by several other environmental factors. More recent studies on benthic foraminifera particularly focus on oxygen and food supply and their availability as factors controlling the living environments of foraminifera (e.g. Murray, 2006). For the Barents Sea these factors also relate to the prevailing water masses (Wassmann *et al.*, 2008), and in particular food availability and quality. This could be of great importance since the primary production in our study area varies from 90 g C m^{-2} yr^{-1} in the area of Atlantic water and <40 g C m^{-2} yr^{-1} near to the Polar front (Sakshaug & Slagstad, 1992; Fig. 1).

5. Conclusions

In this study we have combined recent assemblages of a selection of 20 species of live benthic foraminifera with assemblages of the same 20 species both of live and dead (total) foraminifera in the Barents Sea. We have discussed the applicability of such a combination for tracking environmental change in the benthic foraminifera record, and the linkage of modern and fossil foraminiferal assemblage data.

Regarding the comparison of total and live assemblages, our results indicate that: i) the difference between the two datasets (total and live fauna) is of equal size to the variability within the total fauna dataset, indicating that the selection of the 20 most abundant species eliminates much of the possible error due to method differences; ii) the similar variability of the live and total fauna assemblages indicates that the total assemblages represent short time periods with respect to the temporal sample spacing; iii) the variability within the total fauna samples and between the total and live fauna samples shows a very similar spatial pattern, corroborating the validity of the comparison; only part of this variation is likely due to differences in the abundance of calcareous species, and the total time coverage at each locality; iv) lumping morphologically similar species with different robustness and/or environmental preferences reduces the comparability of total and live fauna; v) grouping species into groups with specific environmental preferences does not impair the similarity between the total and live fauna datasets; vi) the change in abundances of rare species between the two datasets is significant, which may be due to the difference in approach rather than to increased environmental change.

We therefore conclude that it is possible to use total and live fauna in combination in (palaeo-) environmental studies. We advise a restriction be made to species that are abundant in the total faunal assemblages, as this limits the errors involved. We further advise an objective, i.e. quantitative, check being performed on the comparability of the data, e.g. using the Bray-Curtis Index of dissimilarity.

Assuming that the use of the total and live faunal assemblages as equivalents is valid, we can conclude the following regarding the faunal patterns in the central Barents Sea: i) the benthic foraminiferal assemblages in the central Barents Sea display clearly distinguishable faunal provinces, which are comparable to earlier findings; ii) monitoring fluctuations in the abundance of foraminifera species groups with similar environmental preferences yields more promising results in tracking environmental change than monitoring species separately; iii) highest variability in both the 20 species and 3 species groups is found at localities 449 and 350, which is not an artefact of temporal sample spacing or the small number of specimens; iv) large changes at localities 449 and 350 may be related to changes in the properties of inflowing Atlantic Water and the polar front, respectively; v) the observed trends in abundance of species groups agrees fairly well with environmental data; vi) in the study area, the cold water species are in general becoming less abundant while the warm water species show an increase in abundance over the period studied (1971-2006); vii) the link between the faunal and environmental data improves when the restriction of only using species that are abundant in the total fauna is applied more strictly; viii) the fit of faunal and environmental data is weakest at the locality with the highest variability, possibly due to faunal disequilibrium.

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