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DOES THE RECENT POOL OF BENTHIC FORAMINIFERAL TESTS IN FJORDIC SURFACE SEDIMENTS REFLECT INTERANNUAL ENVIRONMENTAL CHANGES? THE RESOLUTION LIMIT OF THE FORAMINIFERAL RECORD

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Abstract: Benthic foraminifera tests (living + dead) and conductivity, temperature and depth (CTD) records in Hornsund Fjord (SW Spitsbergen) were studied over five non-consecutive summer seasons during 2002–2011. The data indicated significant changes in the abundance of benthic foraminifera, species composition and the variability of hydrological and micro-environmental conditions in this fjord. The increased inflow of Atlantic Water (AW) resulted in higher foraminiferal biodiversity and a greater number of rare species; however, many of these were fragile and were thus poorly preserved in the sediment. Cold years significantly reduced species richness in the fjord centre, while more stable hydrological conditions with a predominance of opportunistic foraminifera were noted at the fjord head. *Elphidium excavatum* f. *clavata* and *Cassidulina reniforme* exhibited sensitivity to salinity changes and food supply. The dynamic foraminiferal response to hydrological changes led to the conclusion that the annual foraminiferal flux, compounded by the poor preservation of fragile individuals, significantly changed the spatial and interannual composition of the foraminiferal tests remaining in the sediment. Furthermore, only mature individuals are representative of yearlong or multi-year fjord conditions, since the juveniles that bloom during their maximum growth periods in spring can die out under poor summer and winter conditions. The findings of this study indicated that the upper 8 cm of the sediment in the intense depositional systems of the Svalbard fjords provide good representation of recently departed benthic foraminifera, because of their mobility in surface sediments and further sediment compaction. Hence, the corresponding 10- to 15-year resolution in palaeoceanographic investigations seems to be the most reliable.

Key words: Benthic foraminifera, Hornsund, fjord, hydrology, interannual changes, palaeoceanography.

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INTRODUCTION

Benthic foraminifera are commonly used as proxies for palaeoenvironmental conditions. Therefore, modern studies that compare faunas with environmental data lay the foundation for the use of fossil assemblages in palaeoenvironmental interpretations.

Most of the palaeoenvironmental studies performed in the Svalbard fjords have been based on sedimentary records with a focus on post-glacial processes (Elverhøi *et al.*, 1995; Hald *et al.*, 2001, 2004; Forwick and Vorren, 2009; Łącka *et al.*, 2015) or on short-term, decadal or centennial changes (Zajączkowski *et al.*, 2004; Majewski and Zajączkowski, 2007; Majewski *et al.*, 2009; Szczuciński and Zajączkowski, 2009). Hald *et al.* (2004) and Majewski *et al.* (2009) drew attention to the difficulties in interpreting foraminifera as environmental proxies. These arose from the subtle volatility of the species composition seen at the level of changes in assemblages. However, because of their great abundance in Arctic fjords and shelf settings, benthic foraminifera are crucial as marine environmental indicators (Jennings and Helgadottir, 1994; Korsun *et al.*, 1995; Hald and Korsun, 1997; Polyak *et al.*, 2002; Pogodina, 2005; Lloyd, 2006). Studies on modern benthic foraminifera in the Svalbard fjords were widely conducted at different European research centres (Korsun *et al.*, 1995; Hald and Korsun, 1997; Korsun and Hald, 2000; Ivanova *et al.*, 2008; Rasmussen and Thomsen, 2009; Zajączkowski *et al.*, 2010) including the foraminifera dynamics in the Greenland fjords (Jennings and Helgadottir, 1994) and Novaya Zemlya (Korsun and Hald, 1998). However, most of these studies focused on the occurrence patterns of foraminifera in relation to

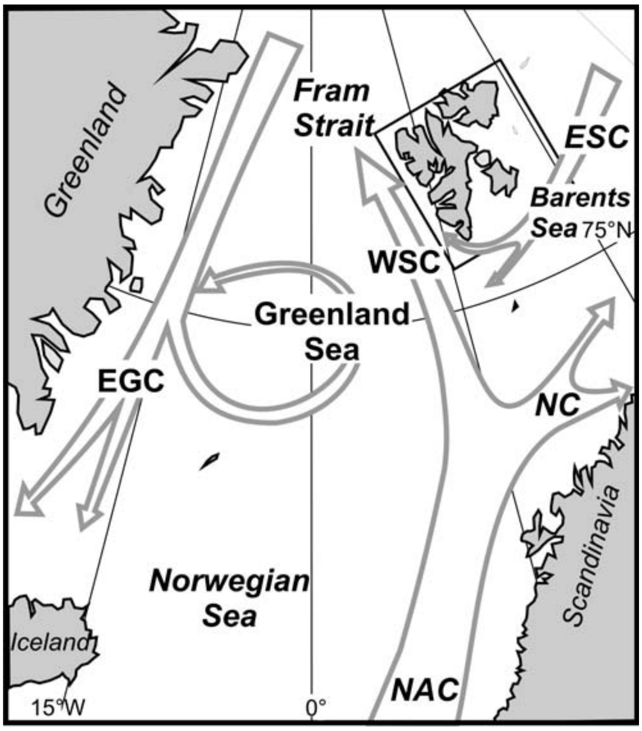

Fig. 1. Sea surface currents in the European Arctic (AMAP, 1998). Norwegian Atlantic Current – NAC, West Spitsbergen Current – WSC, Nordkapp Current – NC, East Greenland Current – EGC. Svalbard (without Bjørnøya) is indicated by the black box.

Table 1

Definition of water masses in Hornsund and on the adjacent shelf (after Cottier *et al*., 2005)

Water Mass	Abbrevia-tion	Characteristic		
		Temperature (°C)	Salinity (PSU)	Density
Atlantic Water	AW	>3.0	>34.65	<27.92
Arctic Water	ArW	–1.5 to 1.0	34.30 to 34.80	
Winter Cooled Water	WCW	<–0.5	34.40 to 35.00	
Local Water	LW	–0.5 to 1.0	34.30 to 34.85	
Surface Water	SW	>1.0	<34.00	
Transformed Atlantic Water	TAW	1.0 to 3.0	>34.65	<27.92
Intermediate Water	IW	>1.0	34.00 to 34.65	

the prevailing conditions in the sampling areas. Hence, the reconstruction of high-resolution palaeoclimate records in the Arctic using benthic foraminifera requires detailed study of the temporal variability on annual and seasonal scales (Jernas, 2012).

The uncompacted upper part of the sediment with high water content contains a foraminiferal assemblage, representing a few to several years of foraminiferal flux (depending on the sedimentation rate) that is reduced by the number of poorly preserved or unpreserved individuals. The habitat depth of many of them depends on food availability, oxygen content and sediment bioturbation (Jorissen *et al.*, 1995; Kaminski *et al.*, 1995; Gooday, 2003). Furthermore, the foraminiferal pool in the upper layer of sediment is enriched yearly with the current year's foraminiferal production. Over time, the compacted layer of sediment preserves the patchiness in the composition of foraminiferal species, limiting the resolution of foraminiferal data (Martin *et al.*, 1996). Thus, the use of a total assemblage (living + dead organisms) instead of only living (stained) organisms gives integrated information on seasonal and spatial variations over a given period of time and provides useful information for palaeoenvironmental interpretations (Scott and Medioli, 1980; Morvan *et al*., 2006).

The aim of the present study was to trace the changes in the composition of benthic foraminiferal species and their quantity and biodiversity along the axis of the Hornsund Fjord over five non-consecutive summer seasons in the period 2002–2011. Since the entire pool of foraminiferal tests potentially corresponds to a fossil assemblage, the authors decided to analyze living and dead organisms in upper 8 cm of the sediment. Foraminiferal data are presented in relationship to the interannual variability of Hornsund hydrology.

OCEANOGRAPHIC SETTING

Hornsund, 32 km long and 10 km wide, is the most southerly fjord in western Spitsbergen (Fig. 2). The deepest basin located in the fjord centre exceeds 260 m; however, the average depth amounts to around 90 m. Three inner bays, Brepollen, Burgerbukta, and Samarinvågen, are more than 100 m deep and are separated from the centre of the fjord by underwater sills. According to Hagen (1993), 73.4% of the fjord catchment area is covered by glaciers that comprise thirteen tidewater fronts. All of them retreated during the last century, exposing almost 20% of the fjord area. The high sediment accumulation rate in the glacier-contact setting of tens of centimeters annually results from the discharge of turbid meltwater at the glacier fronts (Görlich *et al.*, 1987). However, along the fjord axis from the mouth to the head, sediment accumulation varies from 0.5 to 0.7 cm yr^{-1}, respectively (Glud *et al.*, 1998; Szczuciński *et al.*, 2006).

The hydrology of Hornsund Fjord, as well as that of many western Spitsbergen fjords, is characterized by three water masses: external, internal, and mixed (Cottier *et al.*, 2005). The characteristics of these water masses (temperature, salinity, density) are presented in Table 1. Atlantic Water (AW) is transported by the West Spitsbergen Current (WSC) flowing northward and carrying warm, saline water from the North Atlantic (Fig. 1). Arctic Water (ArW) carried by the East Spitsbergen Current is colder and fresher than the AW (Haarpaintner *et al*., 2001). The AW and ArW mix, forming Transformed Atlantic Water (TAW) on the western Spitsbergen shelf. The hydrology of the shelf at the mouth of Hornsund differs from that of most of the shelf sites to the north along the west coast of Spitsbergen, since it is more influenced by ArW. Although the mouth of Hornsund is wide open to the Greenland Sea, the inflow of TAW into the fjord is restricted to the 0–140 m layer because of shallowness (Fig. 2)

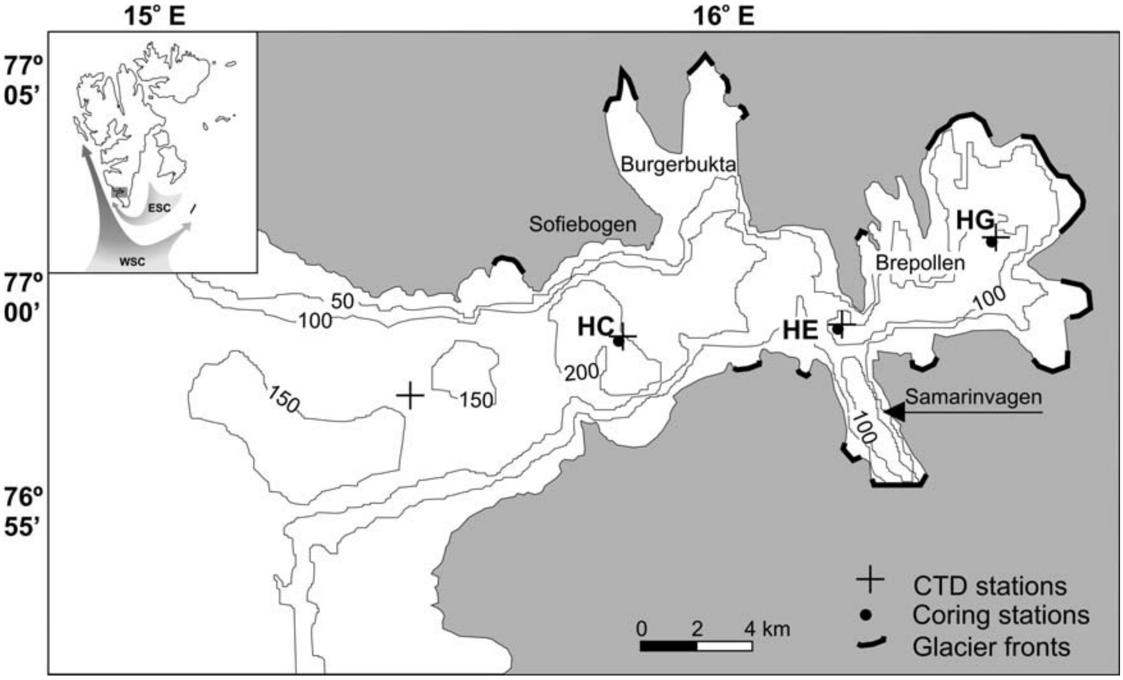

Fig. 2. Study area and sampling station locations. Inset map shows the location of Hornsund Fjord in the Svalbard Archipelago.

Meltwater from glaciers and river runoff form brackish Surface Water (SW), which prevailed in the fjords from the late spring to the fall. The volume of fresh water in Hornsund was estimated at 0.79 km^3 in the summer, but only 40–50 % of this water came from glaciers, while the rest was from less saline ArW from the Barents Sea (Beszczyńska-Möller *et al*., 1997). The thin layer of surface brackish water spread through the fjord with the tides and wind conditions, causing high variability in water temperature, salinity, and turbidity within a short time cycle.

Intermediate Water (IW) is formed when AW and TAW mix with SW, giving rise to a mass that is less saline than the TAW. Local Water (LW) is produced directly in the fjord by convectional processes during the fall and winter cooling. It is also formed near glacier fronts, when warmer water flowing along ice cliffs cools gradually and slowly sinks (Svendsen *et al*., 2002). During freezing in the winter, very saline, cold water called Winter Cooled Water (WCW) forms. The WCW can occupy isolated bottom depressions throughout the year (e.g., Brepollen) and this process is analogous to the formation of brine in Storfjorden (Quadfasel *et al*., 1988; Piechura, 1996).

MATERIALS AND METHODS

The hydrological properties (conductivity, temperature and depth) of the water were measured with a Sea-Bird CTD SBE 49 from aboard the R/V *Oceania* in August of 2002, 2005, 2009, and 2011 and with a Sensordata CTD SD 200 in 2004. The measurements were conducted in four basins: the outer fjord mouth, the fjord centre, the upper fjord, and the fjord head at Brepollen glacial bay (Fig. 2). The exception was in 2004, when measurements were taken in the mouth and the head of the fjord.

Table 2

List of sampling stations in Hornsund Fjord

Station	Latitude	Longitude	Water depth [m]
HC	76°58.43898′N	15°51.1968′ E	203
HE	76°58.81002′ N	16°12.132′ E	106
HG	77°0.73098′ N	16°29.205′ E	138

Fourteen sediment samples were retrieved with a box corer at three locations: the fjord centre (HC), the upper fjord (HE) and at the fjord head (HG). The exception was in 2005, when box cores were retrieved only in the fjord centre and at the fjord head. The upper 8 cm of the sediment (ca. 10–15 years old) were sub-sampled, using a plastic tube with a 7 cm internal diameter (Table 2). The sub-sampled sediment was then homogenized and frozen at –20 °C.

The foraminiferal samples were prepared, following the methods in Feyling-Hanssen (1958) and Meldgaard and Knudsen (1979). In the present study, the authors analyzed the total benthic foraminiferal assemblage without distinguishing between living and dead individuals. All of the samples were wet-sieved through a mesh with diameters of 500 µm and 100 µm (Hald and Korsun, 1997) and then split on a dry micro-splitter. At least 300 individuals of foraminifera were selected from each sample and transferred to micropalaeontological slides. Species identification was perormed with a stereo-microscope and supported by the classification by Loeblich and Tappan (1987) with a few exceptions. The foraminiferal data were expressed as the number of individuals per 10 g of sediment (Appendix 1), percentage values of indicator species, and the ratio of calcareous to agglutinated species. The biodiversity indices were calculated using the Primer 6 software package (PRI-

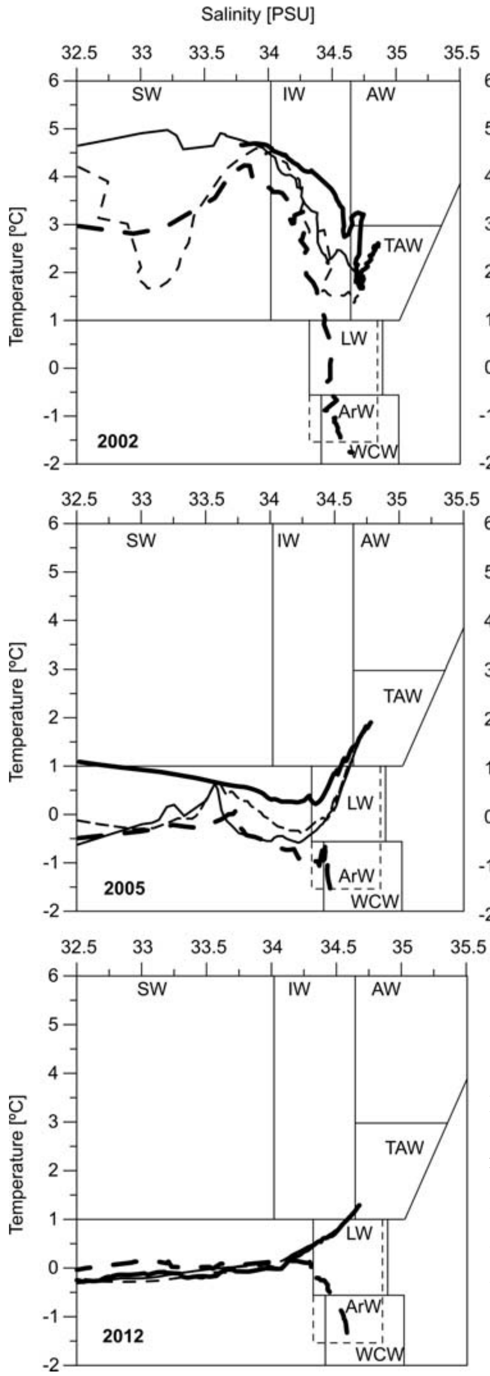

Fig. 3. Temperature-salinity diagrams at four stations in August from five non-consecutive years in the 2002–2011 period (water masses off West Spitsbergen after Cottier *et al.*, 2005) designated as follows: fjord mouth – thick solid line; fjord centre – thin dashed line; upper fjord – thin solid line; Brepollen fjord head – thick dashed line. Data on brackish water (32.5) are not included in the graphs.

MER-E, 2006), using the total number of species (S), Margalef's species richness index (d), and Simpson's diversity index (D). Margalef's index was calculated with the following equation:

$$d = \frac{(S-1)}{\log(N)} \qquad 1$$

where N is the total number of individuals, and S is the number of foraminiferal species noted at the station investigated, with a higher index reflecting greater diversity (Margalef, 1958). Simpson's index was expressed as:

$$D = \sum_{i=1}^{S} \frac{n_i(n_i-1)}{N(N-1)} \qquad 2$$

where S is the number of foraminiferal species, n_i is the number of individuals of the i^{th} species and N is the total number of all individuals. Additionally, rare species were examined, with rarity defined as the number of species with a percentage occurrence of <2.

RESULTS

Hornsund hydrology

The CTD data collected in Hornsund Fjord in August during the period 2002-2011 present considerable inter-annual variation in hydrography. The data were plotted on a T-S diagram (Fig. 3). Brackish surface water (salinity <32.5) was disregarded because of its instability. In 2002

Table 3

Biodiversity indices

		Number of species (S)	Margalef's richness index (d)	Simpson diversity index (D)
2002	HC	32	4.65	0.85
	HE	32	4.90	0.72
	HG	18	4.58	0.79
2004	HC	25	3.99	0.73
	HE	20	3.80	0.63
	HG	9	100.33	9.62
2005	HC	24	3.59	0.83
	HG	14	16.15	1.37
2009	HC	23	3.34	0.82
	HE	28	3.36	0.70
	HG	25	4.30	0.62
2011	HC	11	2.48	0.72
	HE	11	2.57	0.69
	HG	13	2.68	0.80

and 2009, the outer and central parts of Hornsund were occupied by Transformed Atlantic Water (TAW), with a salinity of 34.7 and with a temperature range of 3–4.75 °C. Significant cooling took place in the summer seasons of 2004, 2005, and 2011, when the water temperature decreased and ranged from –1.5 to 1.25 °C. In these cold seasons, temperatures below 0 °C were observed throughout the water column in the centre and at the head of the fjord, but the CTD data show Hornsund hydrological conditions only in early August. In 2004 and 2011, low water temperatures resulted from the inflow of pack ice that covered the fjord from the middle of July to the first week of August. In the summer of 2005, pack ice was not present in Hornsund; thus, the low temperatures reflect the inflow of ArW into the fjord.

The glaciated environment of Brepollen is characterized by a relatively stable bottom water regime throughout the seasons studied with Winter Cooled Water (WCW) dominating near the bottom. The lowest summer temperature of 1.8 °C in Brepollen was observed in 2002 near the bottom. This reflected the high production of brine-enriched waters during fast ice formation and winter mixing throughout the water column. However, a slightly lower salinity was observed in the near-bottom water layer in the 2005 and 2009 seasons, which is probably related to the less intensive fast ice formation in winter.

Benthic foraminifera

A total of 4,545 individuals of benthic foraminifera were identified in the 14 sediment samples (Appendix 1). They represented 64 species (51 calcareous and 13 agglutinated). Most of them were calcareous taxa (over 74% in each sample), while the majority of agglutinated foraminifera individuals (up to 25%) occurred in samples from seasons in 2002 and 2009, collected at the fjord centre, at station HC (Fig. 4).

The total foraminiferal abundance was higher in the fjord centre than in the inner part and was also highest in the 2002 and 2009 seasons at maximums of 788 individuals per 10 g of sediment. The number of foraminiferal individuals decreased at the glacier-proximal site of Brepollen to the minimal value of a single individual per 10 g of sediment, in 2004 (Fig. 4).

Elphidium excavatum f. *clavata* Cushman dominated in the central and upper part of Hornsund, while *Cassidulina reniforme* Nørvangi represented over 50% of the total benthic foraminiferal fauna only once in 2009, in the inner part of the fjord (Fig. 5). The most abundant species in seasons 2004 and 2011 at station HG was *E. excavatum* f. *clavata* (~43% and ~40%, respectively) instead of *C. reniforme* (~15 and ~6%, respectively). Other common species at stations HC and HE were *Nonionellina labradorica* (Dawson), *Buccella frigida* (Cushman), and the agglutinated *Recurvoides turbinatus* (Brady; Fig. 5). Only in 2005, in the central fjord did *Elphidium albiumbillicatum* (Weiss) reach 18.75%, but in the other seasons studied the percentage of this species did not exceed 0.46%. At Brepollen in the fjord head, two agglutinated foraminifers, *Spiroplectammina biformis* (Parker and Jones) and *Textularia earlandi* Parker, were most abundant and the calcareous *N. labradorica* and *Cibicides lobatulus* (Walker and Jacob) were observed throughout the time frame of the study. *Triloculina oblonga* (Montagu) was the most abundant species in 2002 (~42%), but it was very rare in other samples (Appendix 1).

The majority of species were observed in the samples from the fjord centre (20 species/sample) with two exceptions (Table 3). In 2009, the highest number of over 20 species per sample was noted at each station, with most of them in the upper fjord. The number of species (S) in 2011 was as low as 11 in the central and upper fjord and reached 13 in the glacial bay. The highest species richness, according to Margalef's index, was observed in 2004 and in 2005 at station HG (100.33 and 16.15, respectively). The foraminiferal abundance in these samples was the lowest, but most of the organisms represented different species. Simpson's diversity index was the highest in the 2004 and 2005 seasons in the fjord head.

Rare species made a significantly higher contribution (up to 15 species/sample) in the fjord centre (Fig. 6), while in the upper fjord they were represented by a numerous group of taxa (15 and 16) only in the seasons of 2002 and 2009, respectively. In the head of fjord, they comprised 12 species only in 2009, while in the season of 2011 the number of rare species was the lowest, at a maximum of 4 in the fjord head.

DISCUSSION

The data presented indicate significant changes in the abundance of benthic foraminifera tests and their species composition (Appendix 1). Also the hydrological conditions of the Hornsund Fjord show significant interannual variability during the period 2002–2011 (Fig. 3). Nearly complete water exchange occurs in Hornsund from year to year (Renaud *et al.*, 2007). The water on the western Spitsbergen shelf shifts from being dominated by Arctic Water to

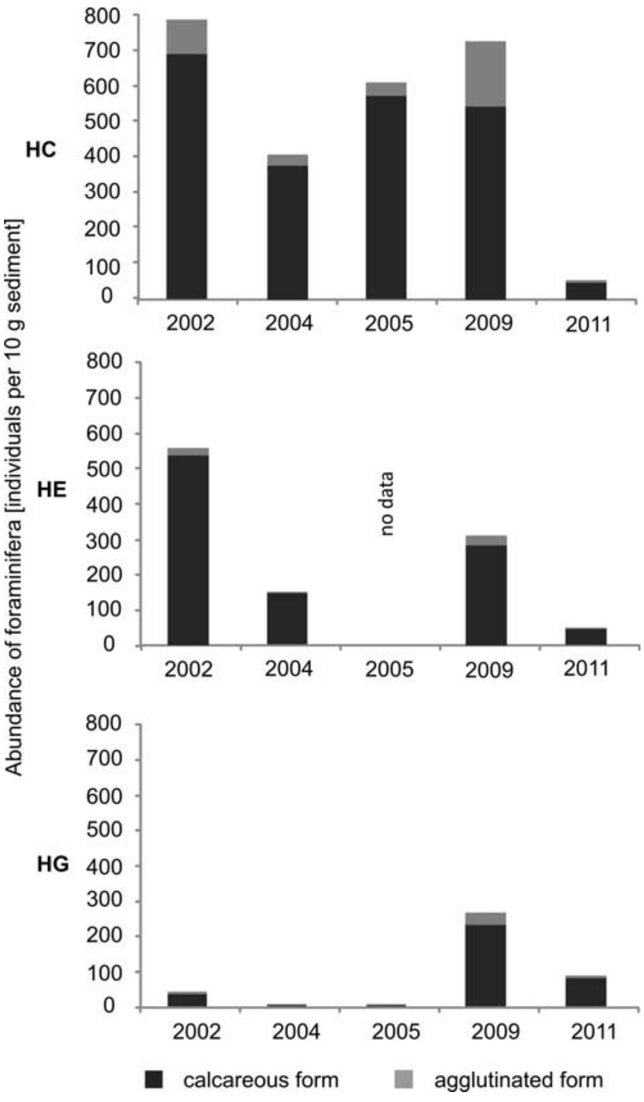

Fig. 4. Abundance of total foraminifera individuals per 10 g of sediment and percentage of agglutinated and calcareous species in years studied.

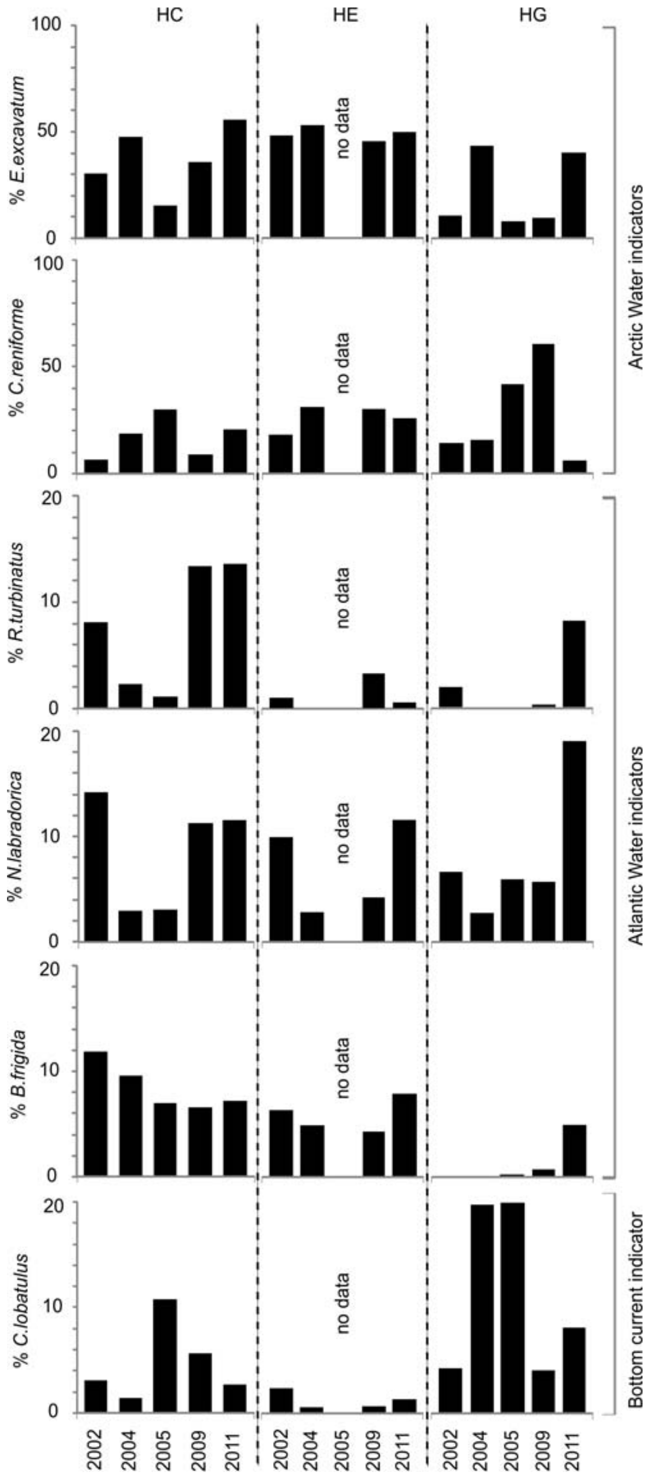

Fig. 5. Percentage of the most abundant foraminiferal species at three sampling stations (HC, HE, HG) in seasons from 2002 to 2011.

Atlantic Water and then back again (Svendsen *et al.*, 2002; Cottier *et al.*, 2005). Such hydrological and micro-environmental variations affect living foraminiferal assemblages (Scott and Medioli, 1980). Since the life span of benthic foraminifera is relatively short, e.g. the *E. excavatum* f. *clavata* life span ranges from a few months to one year (Murray, 1991; Thomas *et al.*, 2000), the decision was taken to analyze the entire foraminifera inventory without distinguishing between living (stained) and dead individuals. Scott and Medioli (1980) and Morvan *et al.* (2006) suggested that this method may help integrate seasonal and spatial variations into a reliable overview of prevailing marine conditions. Moreover, the authors believe that the total foraminiferal inventory reflects the dynamic fjord environment of the last few years, since the habitat depth of various foraminiferal species is variable, and their maximum occurrence can extend to several centimeters below the sediment surface (Ivanova *et al.*, 2008). In Hornsund, according to Zajączkowski *et al.* (2010), the maximum frequencies of modern foraminifera are noted in the 2–8 cm sediment layer. This finding, which results from surface sediment bioturbation, oxygen content, and food availability (Gooday, 2003), led the authors to study the upper 8 cm sediment layer, corresponding to about a decade of sediment accumulation and foraminifera flux.

In the summer seasons of 2002 and 2009, AW dominated throughout the fjord, except in the near-bottom layer in Brepollen (Fig. 3). The warm seasons 2002 and 2009 in-

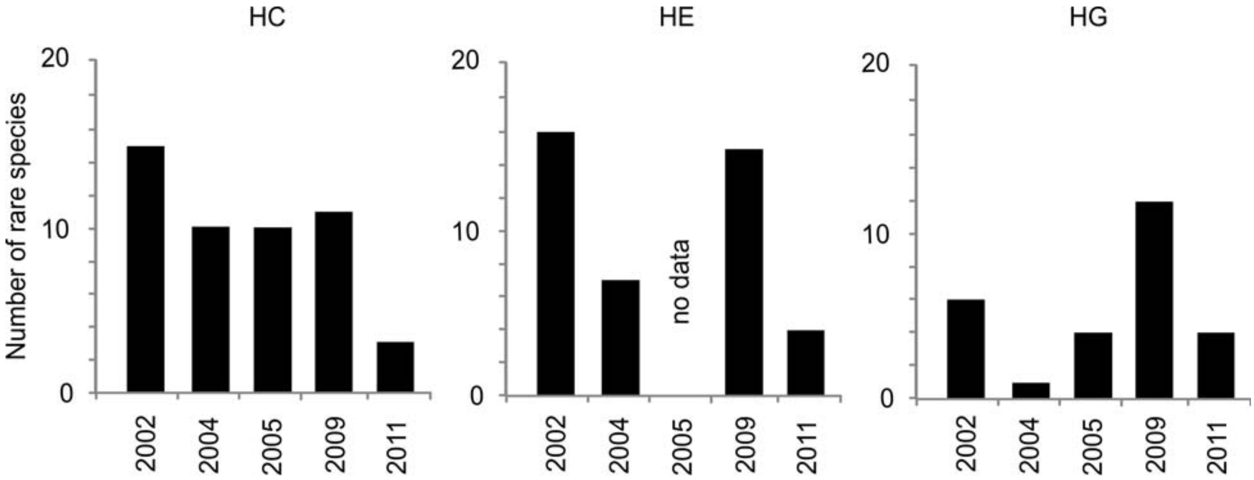

Fig. 6. Sum total of rare species (2% per sample).

dicated the significance of AW, resulting in the predominance of *Elphidium excavatum* f. *clavata*, *Recurvoides turbinatus*, and *Nonionellina labradorica* in both of these warm seasons (Fig. 6). *E. excavatum* f. *clavata* is an opportunistic taxon that typically occurs under strongly fluctuating environmental conditions and it is a dominant taxon, together with *Cassidulina reniforme* (Hald *et al.*, 1994; Knudsen *et al.,* 2012). However, the data of the present authors indicate that the latter species was less abundant in the Hornsund except for the fjord head, in 2009. The next two most numerous species, *R. turbinatus* and *N. labradorica*, are associated with AW. Hald and Korsun (1997) described *R. turbinatus* as a species that is linked to the warmer waters transported by the West Spitsbergen Current. The high number of *N. labradorica* indicates the proximity of the Atlantic Coastal Front (Steinsund, 1994). *N. labradorica* prefers the temperate, saline Transformed Atlantic Water that occupies the deeper, outer, and middle parts of the western Spitsbergen fjords (Hald and Korsun, 1997) and it is used as an indicator of high-productivity settings (Lloyd *et al.*, 2007).

The CTD data from August of 2004, 2005 and 2011 indicate that central and upper Hornsund was dominated by cold, less saline water masses (Fig. 3). In the 2004 and 2011 seasons, pack ice blocked almost all of the Hornsund area for two weeks from the end of July to the beginning of August, causing significant cooling throughout the water column. The authors conclude that the cooling occurred only in the second part of the summer, which could explain the high number of *N. labradorica* throughout the fjord and *R. turbinatus* in the central fjord in August 2011 (Fig. 5). In the opinion of the authors, both of these species, which are related to AW and a large food supply, grew during the spring and the beginning of summer, when the influence of AW was higher and thus the primary production was also higher. This finding is consistent with the conclusion drawn by Zajączkowski *et al.* (2010) that the oxygen isotope record of *N. labradorica* reflects spring conditions in Hornsund. Jernas (2012) found out that *R. turbinatus* has its maximum abundance during early spring, while it decreases significantly in the summer and autumn. The same studies reveal the highest frequencies of *N. labradorica* in the spring.

The abundance of foraminifera in the upper fjord was lower than in the fjord centre (Fig. 4). This difference was significantly higher in cold seasons, when most of agglutinated taxa nearly disappeared from the surface sediments in the upper fjord. The centre and upper fjord were dominated by *E. excavatum* f. *clavata* (45–52%) and *C. reniforme* (18–30%); however, the percentage of the latter increased during seasons of stronger AW influence in the fjord head (Fig. 5). The current results are supported by a study conducted in Hornsund by Hald and Korsun (1997) in August 1990– 1991, when relatively warm water resulted in an increase of *C. reniforme* (77.1%) domination over *E. excavatum* f. *clavata* (13.6%). *C. reniforme* requires fresh food supplies at least once a year and slightly less saline Local and Intermediate Waters, while *E. excavatum* f. *clavata* better tolerates strong salinity fluctuation (e.g., Hald and Korsun, 1997). The relatively high percentage of *C. reniforme* in the fjord head in 2009 coincides with large number of rare species (see Fig. 6). The data collected for the present study indicate that the relative ratio of these two most common, opportunistic species could be used as an indicator of fine- scale hydrological changes in fjords, as discussed in the next paragraph.

While the hydrology and foraminifera occurrence in the centre and upper Hornsund areas changed from season to season, the conditions in the Brepollen glacier bay were more stable. WCW was present throughout the seasons studied and resulted in negative temperatures near the bottom (Fig. 3). However, in the 2005 and 2009 seasons, the salinity of the near-bottom water was slightly lower than that in the other seasons studied, which resulted in two-fold and three-fold increases in *C. reniforme* percentages, respectively (Fig. 5). The authors postulate that this small decrease of WCW salinity probably occurred from the less prominent fast-ice formation in the winter at the fjord head and/or increased inflow of shelf water to Brepollen.

The authors propose that the changes in foraminiferal occurrence and species composition are probably related to spring reproduction and fjord productivity and that subsequent foraminifer growth is supported and/or reduced by the dynamic fjord conditions. Foraminifera propagules

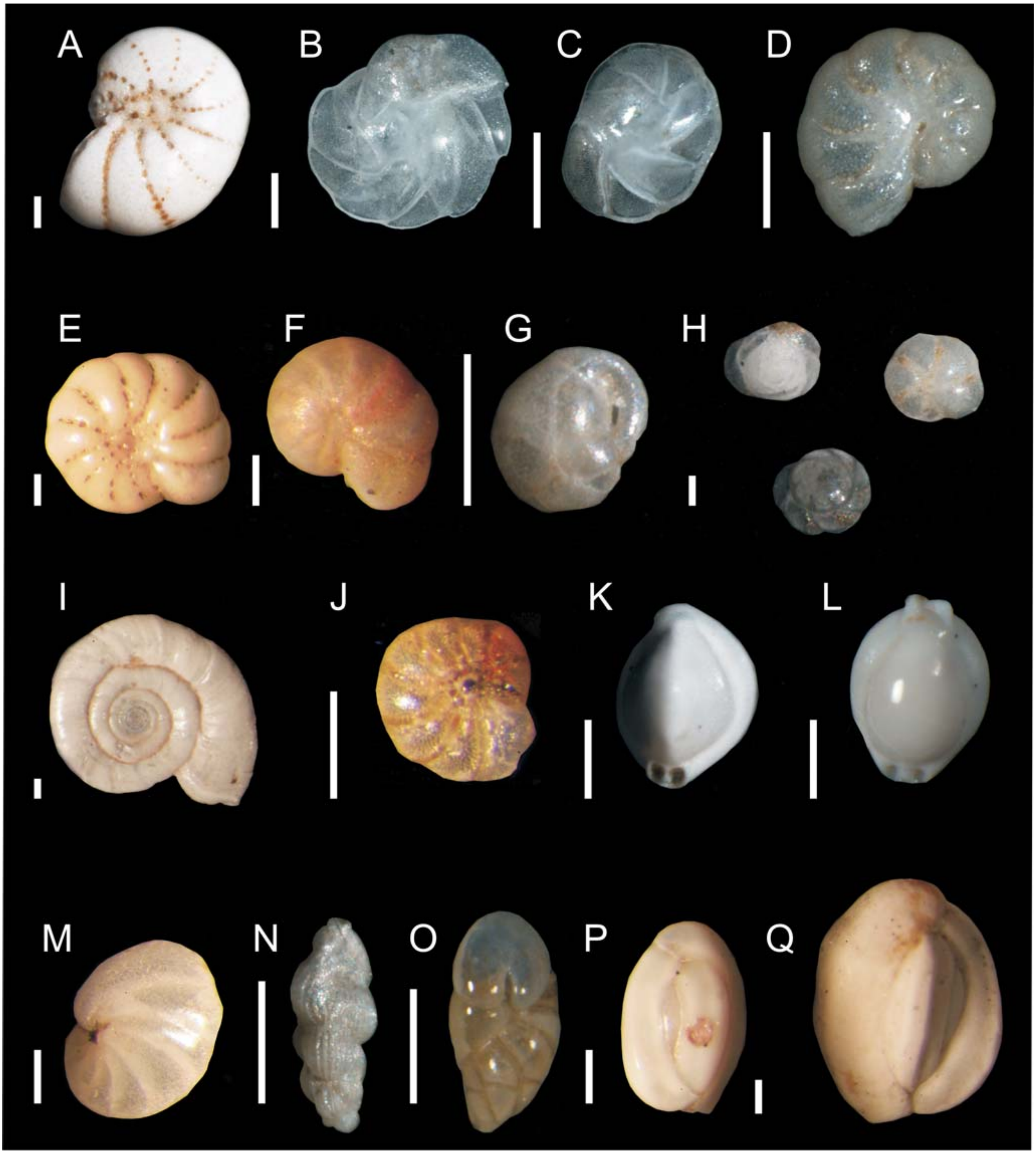

Fig. 7. Digital images of the most abundant calcareous species. Scale bars equal 100 µm. **A.** *Elphidium bartletti* Cushman, 1933. **B.** *Islandiella helenae* Feyling-Hanssen and Buzas, 1976. **C.** *Islandiella norcrossi* (Cushman, 1933). **D.** *Astrononion gallowayi* Loeblich and Tappan, 1953. **E.** *Elphidium asklundi* Brotzen, 1943. **F.** *Cibicides lobatulus* (Walker and Jacob, 1798). **G.** *Cassidulina reniforme* Nørvangi, 1945. **H.** *Buccella frigida* (Cushman, 1921). **I.** *Cornuspira foliacea* (Philippi, 1844). **J.** *Elphidium excavatum* f. *clavata* Cushman, 1930. **K.** *Triloculina frigida* Lagoe, 1977. **L.** *Pyrgo williamsoni* (Silvestri, 1923). **M.** *Nonionellina labradorica* (Dawson, 1860). **N.** *Trifarina fluens* (Todd, 1948). **O.** *Robertinoides charlottensis* (Cushman, 1925). **P.** *Quinqueloculina seminula* (Linnaeus, 1758). **Q.** *Quinquelocu- lina arctica* Cushman, 1933.

undergo passive transport in the water column and subsequently settle onto the bottom sediments (Lang *et al.*, 2012). Therefore, the fine-sediment fractions of many depositional systems contain banks of abundant, diverse foraminiferal propagules that grow to maturity, when the appropriate environmental conditions prevail (Alve and Goldstein, 2003, 2010). Many of the foraminifera species in Hornsund calcify in the spring and summer seasons (Zajączkowski *et al.*, 2010; Jernas, 2012). The fast, clear response of foraminifera to hydrological changes in fjords leads to the assumption that only well-developed, mature individuals reflect the yearlong or multiyear conditions of a particular setting. Immature individuals can grow at the spring food-supply maximum during the phytoplankton bloom, only to wither under poor summer and/or winter conditions. Benthic foraminifera analyses are often performed on various sizes of foraminifera tests. According to Jennings and Helgadottir (1994), large size classes (125 μm) help to avoid uncertain identification of juvenile individuals and although they provide incomplete foraminiferal species composition, they are more closely related to water masses and reflect more useful palaeoceanographic information than the fine size classes.

The data presented in Table 3 indicate that fjord hydrology influences foraminiferal biodiversity in Hornsund. The higher biodiversity indices noted in warm years indicate the domination of AW, whereas in years when pack ice cooled the entire fjord, foraminiferal biodiversity was slightly higher in the centre and fjord head. This probably results from the low resistance of diverse, but less abundant, boreal species to rough Arctic conditions, while the abundance of opportunistic species increased in upper Hornsund. Moreover, high species richness and diversity indices (d and D) in the 2004 and 2005 seasons in the fjord head resulted from very low foraminiferal abundance, while most of specimens represented different species (Appendix 1). This phenomenon explains the occurrence of rare species. The number of rare foraminiferal species occurring in surface sediments was higher in the seasons, when AW dominated (Fig. 7). The distribution of rare species resulted from the high biodiversity of the AW organic load, and subsequently by foraminiferal exposure to different hydrological conditions. Włodarska-Kowalczuk *et al.* (2012) analyzed rarity among benthos communities in the fjords of western Svalbard, and postulated that species were constantly introduced from offshore pools into the inner fjord; however, many of them were only able to survive for short periods of time. The later study of Włodarska-Kowalczuk *et al.* (2013) provides evidence that the patterns of macrobenthic density, diversity and species composition in a glacial fjords exhibit similar characteristics to those of benthic foraminifera. An experimental study on macrobenthic communities showed that the deposition of terrigenous sediment on marine benthic assemblages resulted in its impoverishment, and the rare species were eliminated first (Lohrer *et al.*, 2004). The majority of rare foraminifera comprise fragile species from the genus *Lagena*, which are less resistant to being buried in sediments (Appendix 1). However, numbers of some rare species can grow periodically to high percentages; for example, *Elphidium albiumbillicatum* became a dominant species in the cold season of 2005 in the centre of Hornsund, probably because of fluctuating near-bottom salinity. Furthermore, *Triloculina oblonga* was noted previously in the surface sediments of the Laptev Sea (Lukina, 2001), but its abundance did not reach 1%; therefore, the reason for its dominance at 42% in the sample from the head of Hornsund in 2002 is unclear (Appendix 1).

CONCLUSIONS

The CTD record from Hornsund Fjord indicates a significant interannual variability in hydrological and microenvironmental conditions. These changes influenced fjord productivity from spring to late summer, inducing significant spatial and temporal variability in the composition and abundance of benthic foraminifera species. Hence, the authors conclude that the recent pool of benthic foraminiferal tests seems to be a good indicator of interannual environmental changes in Hornsund Fjord. However, only well-developed, mature individuals reflect the yearlong or multiyear conditions of a particular setting.

Over time, the compacted layer of sediment presents a foraminiferal assemblage resulting from the interannual hydrological variability of the settings, limiting resolution of the foraminiferal record in the sediment to several years.

The increased inflow of AW resulted in higher foraminifera biodiversity and a greater number of rare species. However, many of them were fragile and were thus badly preserved in subfossil sediments. The exception could be *N. labradorica*, which was abundant in the samples studied in the central fjord and in the ancient sediments at the Hornsund mouth (Majewski *et al.*, 2009). It was confirmed that this species can be used as an AW indicator and as an indicator of high foraminiferal biodiversity and rare benthic foraminifera.

The two most common species *E. excavatum* and *C. reniforme* usually represent more than 50% of all of the foraminifera assemblages in Hornsund. They have been used widely as ArW indicators (e.g., Ślubowska-Woldengen *et al.*, 2007, Majewski *et al.*, 2009), but because of their opportunistic features, they can also tolerate increased inflow of turbid water into ice-proximal settings during warming. Nevertheless, the ratio of these two species could be used as an indicator of fine-scale hydrological changes in fjords, because of their different preferences regarding fluctuation in salinity and food supply.

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Appendix 1. Number of individuals per 10 g sediment

	HC					HE				HG				
Species	2002	2004	2005	2009	2011	2002	2004	2009	2011	2002	2004	2005	2009	2011
Adercotryma glomerata	0.31	–	–	–	–	0.62	–	3.24	–	0.15	–	–	1.84	–
Ammodiscus gullmarensis	–	–	–	–	–	–	0.42	–	–	–	–	–	–	–
Ammotium cassis	3.39	–	–	–	–	4.01	–	0.05	–	–	–	–	–	–
Cibicidoides globulosus	–	–	1.74	–	–	–	–	–	–	–	–	–	–	–
Astrononion gallowayi	3.86	0.72	8.68	–	–	0.15	–	0.41	–	0.15	–	–	1.23	–
Astrononion tumidum	–	–	–	–	–	0.77	–	–	–	–	–	–	–	–
Bolivinellina pseudopunctata	1.54	13.05	–	4.79	–	0.46	0.42	0.81	–	–	–	–	–	–
Buccella frigida	95.81	39.87	43.39	47.93	3.50	35.02	7.13	13.38	3.82	0.46	–	0.01	1.84	4.92
Buccella tenerrima	–	–	–	–	–	–	–	–	–	–	–	–	0.61	–
Cassidulina reniforme	50.91	76.84	182.24	63.90	9.94	99.36	45.69	92.37	12.31	5.71	0.17	0.92	158.90	4.68
Cassidulina obtusa	–	–	–	–	–	0.15	–	–	–	–	–	–	–	–
Cibicides lobatulus	24.69	5.80	65.95	41.59	1.33	13.27	0.84	2.03	0.62	1.70	0.21	0.44	10.43	6.40
Cornuspira foliacea	–	–	–	–	–	0.15	–	–	–	–	–	–	–	–
Cornuspira involvens	–	–	–	3.20	–	–	–	0.42	0.12	–	–	–	–	0.25
Cribrostomoides crassimargo	2.62	3.65	–	1.45	–	2.31	0.12	0.84	–	–	–	–	0.61	–
Dentalina frobisherensis	–	–	–	–	0.25	–	–	–	–	–	–	–	–	–
Cuneata arctica	0.31	0.72	1.74	–	–	–	–	1.62	–	–	–	–	–	–
Verneuilinulla advena	0.31	0.72	17.36	–	–	–	–	0.41	–	–	–	–	–	–
Elphidiella arcitica	–	0.01	–	–	–	–	–	–	–	–	–	–	–	–
Elphidium albiumbilicatum	1.23	–	114.55	–	–	0.31	–	–	–	–	–	–	1.23	–
Elphidium asklundi	–	–	–	–	–	–	–	0.01	–	–	–	–	–	–
Elphidium bartletti	0.15	0.05	6.94	1.60	–	29.78	1.68	10.94	–	–	–	0.01	3.07	–
Elphidium excavatum f. clavata	238.06	195.72	95.46	260.46	26.95	269.54	78.39	141.38	24.00	4.32	0.47	0.18	24.54	32.00
Elphidium excavatum f. selseyensis	98.74	3.62	3.47	–	–	13.73	–	–	–	0.15	–	–	–	–
Elphidium incertum	–	–	–	–	–	–	–	0.01	–	–	–	–	–	–
Elphidium subarcticum	4.17	–	–	–	–	0.15	–	–	–	–	–	–	–	–
Elphidium ustulatum	–	–	6.94	–	–	–	–	–	–	–	0.03	–	–	–
Elphidium orbiculare	–	–	–	–	–	1.70	–	–	–	–	–	–	0.61	–
Fissurina marginata	–	–	6.94	1.60	–	–	–	–	–	–	–	–	–	–
Fissurina serrata	–	–	–	3.20	–	–	–	–	–	–	–	–	–	–
Glandulina laevigata	–	–	1.74	–	–	–	–	0.01	–	–	–	–	–	–
Globobulimina auricula arctica	–	–	–	0.20	–	–	–	–	–	–	–	–	–	1.48
Globobulimina turgida	0.62	–	–	–	–	–	–	–	–	–	–	–	–	–
Guttulina austriaca	–	–	–	–	–	–	–	–	–	–	–	–	1.23	–
Guttulina dawsoni	–	–	–	–	–	–	–	–	–	–	–	–	0.61	–
Guttulina glacialis	–	–	–	–	–	–	–	–	–	–	–	0.02	–	–
Guttulina lactea	–	–	–	–	–	–	–	–	–	–	–	–	0.61	–
Hyperammina subnodosa	11.42	–	–	0.50	–	0.62	–	0.19	–	–	–	–	–	–
Islandiella helenae	4.94	0.72	3.47	3.20	–	5.55	0.42	7.29	–	0.31	0.01	0.03	1.23	0.74
Islandiella islandica	–	7.25	–	–	–	–	0.84	–	–	–	0.02	–	–	–
Islandiella norcrossi	5.40	4.35	–	–	0.05	0.46	–	0.82	1.48	–	–	–	1.23	3.94
Lagena elongata	–	–	–	–	–	–	0.42	–	–	–	0.04	–	0.61	–
Lagena parri	–	–	–	–	–	–	–	–	–	–	–	0.02	–	–
Miliammina agglutinata	3.39	–	–	1.95	–	0.93	–	0.82	–	0.15	–	–	0.61	–
Miliamimna stalkeri	7.25	–	1.74	14.38	–	8.33	–	2.03	–	0.15	–	0.02	4.29	–
Nonionella auricula	–	5.07	–	0.05	–	–	1.26	–	0.12	–	–	–	–	–
Nonionellina labradorica	111.55	12.32	19.09	82.78	5.60	56.01	4.19	12.97	5.66	2.78	0.03	0.13	15.34	19.45
Oolina caudigera	–	–	1.74	–	–	–	–	–	–	–	–	–	–	–
Pyrgo williamsoni	1.85	–	–	–	–	1.08	–	–	–	–	–	–	–	–
Quinqueloculina arctica	5.86	0.12	–	0.25	–	0.93	–	0.01	–	–	–	–	0.61	–

	HC					HE				HG				
Species	2002	2004	2005	2009	2011	2002	2004	2009	2011	2002	2004	2005	2009	2011
Quinqueloculina seminula	29.62	5.07	1.74	11.68	0.35	3.55	0.42	1.63	–	0.31	–	–	–	5.42
Quinqueloculina stalkieri	–	6.52	–	–	–	–	1.26	–	–	–	–	–	–	–
Recurvoides turbinatus	63.72	9.42	6.94	97.60	7.63	5.40	–	10.13	0.26	0.77	–	–	0.61	7.14
Remaneica helgolandica	–	–	3.47	–	–	–	–	–	–	–	–	–	–	–
Robertinoides charlottensis	0.77	–	–	–	0.25	–	–	–	–	–	–	–	–	0.25
Silicosigmoilina groenlandica	–	–	5.21	–	–	–	0.42	0.41	0.12	–	–	–	–	–
Spiroplectammina biformis	3.70	7.25	8.68	35.15	–	0.31	0.42	6.48	–	2.31	–	0.06	12.88	–
Stainforthia loeblichi	0.31	5.80	–	–	–	0.31	0.42	–	–	0.15	–	0.05	4.91	–
Textularia earlandi	1.85	5.07	–	35.15	–	0.62	2.10	–	–	3.86	0.11	0.34	15.34	–
Triloculina oblonga	3.09	–	–	–	–	3.39	1.26	–	–	17.13	–	0.01	–	–
Trifarina fluens	–	–	–	–	0.25	–	–	–	–	–	–	–	–	–
Triloculina frigida	6.79	–	–	17.57	–	0.77	–	0.41	0.25	0.31	–	–	–	0.74
Triloculina trihedra	–	1.45	–	–	–	–	–	–	–	–	–	–	–	–
Trochammina inflata	–	–	1.74	–	–	–	–	–	–	–	–	–	–	–