Biogeosciences Discuss., 9, 7783–7830, 2012
www.biogeosciences-discuss.net/9/7783/2012/
doi:10.5194/bgd-9-7783-2012

Biogeosciences Discussions

The benthic foraminiferal community in a naturally CO_2-rich coastal habitat in the southwestern Baltic Sea

K. Haynert[1], J. Schönfeld[1], I. Polovodova-Asteman[2], and J. Thomsen[1]

[1]Helmholtz Centre for Ocean Research Kiel, GEOMAR, Wischhofstrasse 1–3, 24148 Kiel, Germany
[2]Department of Earth Sciences, University of Gothenburg, P.O. Box 460, 40530 Göteborg, Sweden

Received: 30 April 2012 – Accepted: 14 May 2012 – Published: 27 June 2012

Correspondence to: K. Haynert (khaynert@ifm-geomar.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

It is expected that the calcification of foraminifera will be negatively affected by the ongoing acidification of the oceans. Compared to the open oceans, these organisms are subjected to much more adverse carbonate system conditions in coastal and estuarine environments such as the southwestern Baltic Sea, where benthic foraminifera are abundant. This study documents the seasonal changes of carbonate chemistry and the ensuing response of the foraminiferal community with bi-monthly resolution in Flensburg Fjord. In comparison to the surface pCO_2, which is close to equilibrium with the atmosphere, we observed large seasonal fluctuations of pCO_2 in the bottom and sediment pore waters. The sediment pore water pCO_2 was constantly high during the entire year ranging from 1244 to 3324 µatm. Nevertheless, in contrast to the bottom water, sediment pore water was slightly supersaturated with respect to calcite as consequence of higher alkalinity (A_T) for the most time of the year. Foraminiferal assemblages were dominated by two calcareous species, *Ammonia aomoriensis* and *Elphidium incertum*, and the agglutinated *Ammotium cassis*. The one year-cycle was characterized by seasonal community shifts. Our results revealed that there is no dynamic response of foraminiferal population density and diversity to elevated sediment pore water pCO_2. Surprisingly, the fluctuations of sediment pore water undersaturation (Ω_{calc}) co-vary with the population densities of living *Ammonia aomoriensis*. Further, we observed that most of the tests of living calcifying specimens were intact. Only *Ammonia aomorienis* showed dissolution and recalcification structures on the tests, especially at undersaturated conditions. Therefore, the benthic community is subjected to constantly high pCO_2 and tolerates elevated levels as long as sediment pore water remains supersaturated. Model calculations inferred that increasing atmospheric CO_2 concentrations will finally lead to a perennial undersaturation in sediment pore waters. Whereas benthic foraminifera indeed may cope with a high sediment pore water pCO_2,the steady undersaturation of sediment pore waters would likely cause a significant higher mortality of the dominating *Ammonia aomoriensis*. This shift may eventually

lead to changes in the benthic foraminiferal communities in Flensburg Fjord, as well as in other regions experiencing naturally undersaturated Ω_{calc} levels.

1 Introduction

The combustion of fossil fuels leads to rising atmospheric carbon dioxide concentrations, which cause an acidification of the oceans (Zeebe and Wolf-Gladrow, 2001). By 2100, the concentration of the ocean pCO_2 is expected to be approximately 750 µatm (Feely et al., 2004; Raven et al., 2005) and seawater pH is going to decrease by 0.4 units (Caldeira and Wickett, 2005). The reduced saturation state and carbonate ion concentration will cause a reduction in biogenic calcification of predominant organisms like corals, coccolithophorids and foraminifera (Gattuso et al., 1998; Kleypas et al., 1999; Bijma et al., 1999; Riebesell et al., 2000). Consequently, corrosive conditions are expected to affect the formation of carbonate skeletons of calcifying organisms (Erez, 2003; Raven et al., 2005).

Already today, calcifying organisms such as foraminifera are subjected to much more adverse carbonate system conditions in coastal marine environments as compared to the open ocean (Borges and Gypens, 2010). Especially environments such as the western Baltic Sea, which are subjected to a low salinity and alkalinity, are characterised by low carbonate ion concentrations (CO_3^{2-}) and consequently lower calcium carbonate saturation states (Ω_{calc}) (Thomsen et al., 2010). Furthermore, seasonal stratification of water masses, respiration in deeper layers and eutrophication induced summer hypoxia in the bottom water layers. This causes high and variable pCO_2 and consequently low pH during the course of the year (Diaz and Rosenberg, 2008; Conley et al., 2009; Nikulina and Dullo, 2009; Thomsen et al., 2010). In such habitats, ongoing oceanic CO_2 uptake will cause a drastic increase of the prevailing pCO_2 levels with peaks up to 4000 µatm by the year 2100 (Melzner et al., 2012).

Many laboratory studies have shown that calcareous foraminifera exhibited lower calcification rates under simulated future scenarios of high seawater pCO_2(Le Cadre

BGD
9, 7783–7830, 2012

et al., 2003; Kuroyanagi et al., 2009; Allison, 2010; Haynert et al., 2011; Fujita et al., 2011). To date, a low number of field studies reported that calcifying organisms are negatively affected by a high pCO_2 in natural habitats (Fabricius et al., 2011). In proximity to hydrothermal vents, where volcanic CO_2 causes a natural decline of pH, a significant decrease in abundance and species richness of calcareous foraminifera was observed between ambient pH levels of 8.09 to 8.15 and low pH-levels of 7.08 and 7.79 close to the vents (Cigliano et al., 2010; Dias et al., 2010).

Benthic foraminifera are common in the SW Baltic Sea, although seawater carbonate concentrations are permanently low and even seasonally undersaturated (Lutze, 1974; Wefer, 1976; Grobe and Fütterer, 1981; Polovodova et al., 2009; Thomsen et al., 2010; Haynert et al., 2011). Salinity, temperature, oxygen, and food availability were considered as important factors, which regulated the foraminiferal diversity and abundance (e.g. Rottgardt, 1952; Bradshaw, 1957; Lutze, 1965; Wefer, 1976; Alve and Murray, 1999; Frenzel et al., 2005). These studies, however, did not take the impact of seawater carbonate chemistry into account.

Living benthic foraminiferal assemblages in Flensburg Fjord were first described by Exon (1972). Some specimen of *Ammonia aomoriensis* from this area were reported as having thin or opaque shell walls and extremely corroded tests (Polovodova et al., 2009). In some cases, the tests were completely destroyed and only the inner organic lining was left. Abrasion and predation were considered as possible mechanisms for test destruction, but test dissolution due to fluctuated pH has been suggested as the most likely cause for the corroded *Ammonia* tests in that area (Polovodova and Schönfeld, 2008). Indeed, similar signs of test dissolution were observed, when living specimen of *Ammonia aomoriensis* from Flensburg Fjord were exposed to elevated pCO_2 levels from 929 to 3130 µatm in a laboratory experiment (Haynert et al., 2011).

Natural CO_2-rich habitats can serve as valuable example for possible effects on calcifying benthic community structures due to climate change (Hall-Spencer et al., 2008; Thomsen et al., 2010). Our study site in Flensburg Fjord, SW Baltic Sea represents an adequate study area for dynamic response of the foraminiferal fauna to elevated pCO_2.

BGD
9, 7783–7830, 2012

The consequences of naturally CO_2-enriched environments on benthic foraminifera are not sufficiently studied to date.

The aim of this study was to investigate the response of the foraminiferal population dynamics, as well as the variations of species composition and diversity to high pCO_2 and low Ω_{calc} conditions over a one-year cycle. The main focus was on two calcifying species, *Ammonia aomoriensis* and *Elphidium incertum*. An effect of low sediment pore water carbonate saturation on population density and test dissolution of this species has been assessed.

2 Study site and sampling

Flensburg Fjord, located in the southwest of the Baltic Sea (53°41′–55°00′ N; 9°24′–10°10′ E), is a narrow and 50 km long inlet. The Fjord is subdivided into a 10–20 m deep inner fjord which extends from the city Flensburg to Holnis Peninsula. The area from Holnis Peninsula to Neukirchen/Kragesand is a 18–20 m deep middle fjord. The 10–32 m deep outer fjord comprises Soenderborg Bay, Gelting Bay and open waters to the east of Gelting Peninsula.

Sediment and water samples were taken from seven stations (FF1 to FF7) on six bi-monthly cruises with R/V Littorina from June 2009 to April 2010 (Fig. 1). All seven stations (FF1 to FF7) were monitored for water carbonate chemistry. Sediment cores for foraminiferal studies were taken from stations FF1, FF4 and FF5. Station FF1 is located in a shallow near-coastal area, where sandy bottoms prevail (Table 1). At stations FF4 and FF5 muddy sands were encountered (Table 1). The cliff and submarine erosion are predominant sources for sediments, which are transported from the east by long shore drift toward the outer Flensburg Fjord (Exon, 1971).

BGD
9, 7783–7830, 2012

3 Material and methods

3.1 Foraminiferal processing

The foraminiferal communities were studied from surface sediments from stations FF1, FF4 and FF5. Benthic foraminiferal samples were taken with a Mini Muc K/MT 410 corer equipped with tubes of 60 cm length and 10 cm inner diameter. A plastic ring marked with 0.5 cm-scale was used to slice the uppermost one centimetre of the sediment core. A thin grey spatula was gently moved between tube top and the plastic ring. The surface layer of sediment was safely removed from the core and transferred with a spoon into 300 ml Kautex™ wide-neck containers. The sediment was preserved and stained with a Rose Bengal ethanol solution of $2\,g\,l^{-1}$ according to Lutze and Altenbach (1991). Ethanol concentration was 94 %. Staining time was three weeks at minimum, whereby we felt certain that the protoplasm was completely impregnated with Rose Bengal in all test of foraminifera that were living at the time of sampling.

In the laboratory, samples were first passed through a 2000 µm screen in order to remove molluscs shells and pebbles. Subsequently the samples were gently washed with tap water through a 63 µm sieve. The 63–2000 µm and >2000 µm fractions were dried at 60 °C for at least 24 h. Fraction of 63–2000 µm was split by using an Otto (1933) microsplitter to obtain aliquots of a manageable size. They were weighted and quantitatively analysed for living and dead foraminifera. All Rose Bengal stained foraminifera were considered as living at the time of sampling whereas unstained individuals were considered as dead. Living and dead specimens were picked from the respective aliquots, sorted by species, mounted in Plummer cell slides with glue, counted and measured. The dominant species were photographed by using a Scanning Electronic Microscope (Cam Scan-CS-44) at the Institute of Geosciences, Kiel University.

The tests of living *A. aomoriensis* were subdivided into three stages of preservation: intact tests, loss of the last chamber and loss of more than two chambers. The tests were also photographed using a Scanning Electronic Microscope (Cam Scan-CS-44)

BGD
9, 7783–7830, 2012

and Electron Probe Microanalyzer (Jeol JXA-8200 EPMA). Light micrographs were taken with a MiniPixie (MPX2051UC) digital microscope.

3.2 Carbonate chemistry

Temperature and salinity parameters of the surface and near-bottom water were recorded using a CTD48M probe (Sea and Sun Technology) at all stations (Tables 2 and 3). At water chemistry stations, samples for analyses of carbonate chemistry parameters were taken from the surface water at 1 m depth on stations FF1 to FF7 (Table 2), near-bottom water from 1 m above sea floor was taken at stations FF2, FF3, FF6 and FF7. Bottom water approximately 1 cm above the sediment surface and sediment pore water from 0 to 5 cm sediment depth was only collected at foraminifera sampling stations FF1, FF4 and FF5 (Table 3).

Surface and near-bottom water samples were taken using Niskin bottles and filled bubble free into 250 or 500 ml Duran™ glass bottles. Samples were poisoned with 50 or 100 µl saturated mercuric chloride solution and stored at room temperature until analysis. Total alkalinity (A_T) and total inorganic carbon (C_T) of the samples were measured by potentiometric titration using VINDTA autoanalyzer and coulometric titration after CO_2 extraction using the SOMMA system, respectively (Mintrop et al., 2000; Dickson et al., 2007). Offset of total alkalinity (A_T) and total carbon (C_T) determinations (Tables 2 and 3) were assessed and corrected by measurements of certified reference material (Dickson et al., 2003). Seawater pH_{NBS}, pCO_2 and omega for calcite (Ω_{calc}) were calculated by using the CO2Sys-program developed by Lewis and Wallace (1998) (Tables 2 and 3). Dissociation constants K_1 and K_2 were chosen according to Mehrbach et al. (1973) as refitted by Dickson and Millero (1987) and the $KHSO_4$ dissociation constant after Dickson (1990).

Bottom water samples for carbonate system parameters were taken from the supernatant water of Minicorer-tubes and filled directly in 20 ml PVC bottles. For sediment pore water analyses, the sediment cores were sliced in 0.5 cm intervals up to 2 cm depth, below 2 cm the intervals were 1.0 cm up to 5 cm. Sediment samples from each

BGD
9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

interval were transferred to 50 ml centrifuge tubes and centrifuged at 3000 rpm for 30 up to 40 min in order to separate the sediment pore water from the sediment. The extracted sediment pore water and the bottom water were transferred through 0.2 µm steril filters into 20 ml PVC bottles. Bottom and sediment pore water pH_{NBS} were measured using a WTW 340i with a precision of ±0.01. The pH electrode was calibrated using standard buffer solutions of pH 4.01, 7.00 and 10.00 (WTW standard, DIN/NIST buffers L7A). Subsequently, bottom and sediment pore water alkalinity was determined with a Metrohm titration instrument according to Ivanenkov and Lyakhin (1978). A greenish-brown Methyl-Red and Methylene-Blue indicator was added, and titration was performed with 0.02 M HCl and finished until a stable light pink colour occurred. During titration, the sample was degassed by continuously bubbling nitrogen through the solution in order to remove the generated CO_2 or H_2S. The measured values were standardized using an IAPSO seawater solution. The precision of the alkalinity measurements was 0.37 %. The carbonate system parameters of bottom and sediment pore water, total carbon (C_T), pCO_2 and omega for calcite (Ω_{calc}) were calculated from measured pH_{NBS} and total alkalinity (A_T) according to dissociation constants as specified above.

3.3 Data analyses

Shannon diversity (H') according to Shannon (1948a, b) and Fisher's alpha diversity index according to Fisher et al. (1943) were calculated for the living and dead foraminiferal assemblages. The program SmartConservation™ (Version 1.43 6/21/2004) was used for the calculations.

4 Results

4.1 Temperature and salinity

Surface and near-bottom water temperature and salinity from stations FF1 to FF7 in Flensburg Fjord were characterized by pronounced fluctuations, prevailing in the area of the Baltic. Temperature ranged from −0.9 to 20 °C at the surface and from −0.8 to 15.3 °C at the bottom during the investigation period (Tables 2 and 3).

A stable thermocline from 7 to 8 m water depth stratified the water column between June and August 2009. From December 2009 to April 2010, the water column was well mixed with a temperature of 5 °C on average in both, surface and near-bottom water. The surface of Flensburg Fjord was covered by floating ice in February, during that time lowest temperatures were observed, ranging from 0.9 to 1.1 in the surface and near-bottom water (Tables 2 and 3).

Mean salinity ranged from 13.3 to 21.1 at the surface, and 16.8 to 26.3 in the bottom water (Tables 2 and 3). The salinity increased from the surface (15.7) to the near-bottom water (21.4), caused a persistent picnocline from spring to summer. Mixing in October caused a homogenous salinity in the water column of approximately 22. A slight halocline in December caused again to a lower mean salinity of 18.1 in the surface and a higher value of 22.8 in the bottom water (Tables 2 and 3). In February, the boundary layer between the surface and near-bottom water was dissipated and a uniform salinity of 17 was observed.

4.2 Carbonate chemistry

Carbonate chemistry measurements revealed a relatively stable surface pCO_2 during the whole year (Fig. 2a). In contrast, pH and pCO_2 in the bottom and sediment pore water showed a high variability during the seasonal cycle in Flensburg Fjord (Fig. 2b and c).

BGD

9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

Surface pCO_2 (478 ± 197 µatm) was close to atmospheric levels with slightly lower values during the spring bloom, similarly pH (8.13 ± 0.15) was relatively high and stable (Table 2, Fig. 2a). In general, the western Baltic Sea is characterized by a low salinity, ranging from 13 to 21, and consequently a low alkalinity (A_T) of 1821 to 2057 µmol kg^{-1} prevailed in the surface water (Table 2). Consequently, the calcium carbonate saturation state for calcite (Ω_{calc}) was low in this area. During the monitoring, we recorded a mean surface Ω_{calc} of 1.84 ± 0.70 in 2009 and 2010. Undersaturation of the surface water was observed in February, with Ω_{calc} values ranging from 0.40 to 0.94 (Table 2).

Stratification of the water column causes a strong CO_2-accumulation in the bottom water during summer and autumn. Therefore, large seasonal fluctuations of pCO_2, pH and Ω_{calc} were observed in the near- and bottom water. One meter above the sediment, the mean near-bottom water pCO_2 was 1120 ± 82.86 µatm. In comparison, the bottom water pCO_2 (1 cm above sediment) increased to 1390 ± 71.63 µatm (Table 3). Highest pCO_2 levels reached up to 2000 µatm during August in the near-bottom water and up to 3000 µatm during October in the bottom water a few cm above the benthic boundary (Table 3, Fig. 2b). This caused lowest pH values of 7.40 and 7.21 in the near-bottom and bottom waters during August and October (Table 3). After mixing of the water column, pCO_2 decreased in winter to mean values of 550±65.44 µatm and 657±132.07 (Table 3). Similarly, mean pH showed the highest value of 7.91 in the near-bottom water and 7.85 in the bottom water (Table 3). The calculated mean Ω_{calc} values in the near-bottom water (1.08±0.07) and bottom water (1.10±0.05) were low compared to surface Ω_{calc} and varied between the studied stations (Table 3). Flensburg Fjord near-bottom and bottom waters were frequently undersaturated for Ω_{calc} with a lowest value of 0.45 in August and October (Table 3).

The sediment pore water carbonate chemistry strongly deviated from the conditions in the water column. Sediment pore water pCO_2 from the 0 to 1 cm depth-interval, did not fluctuate as strong as the bottom water. It was noticeable that the pCO_2 was high during the whole year and ranged from 1244 to 3324 µatm (Table 4, Fig. 2c). Mean sediment pore water pCO_2 of the 0–1 cm depth-interval was 2013 ± 610 µatm,

BGD
9, 7783–7830, 2012

pH (7.55±0.10) was lower, but more stable in comparison to the water column (Table 4, Fig. 2c). In contrast, the pH-profile of the sediment pore water revealed considerable fluctuations within the 1 and 5 cm depth-interval, ranging from 6.82 to 8.11 (Fig. 3). Furthermore, the pH-fluctuations varied also between the sampling stations and during the seasonal cycle. No trend was observed in the 5 cm depth-interval. Compared to the bottom water A_T (2233 ± 190 µmol kg^{-1}), the sediment pore water alkalinity was much higher (2856 ± 400 µmol kg^{-1}) which causes a relative high, slightly supersaturated Ω_{calc} of 1.09 ± 0.38 (Table 4, Fig. 2d). Only sediments at station FF4 were consistently undersaturated for Ω_{calc} with the lowest value of 0.46 in February (Table 4, Fig. 2d).

4.3 Foraminiferal population density and species composition

Population density of the living foraminiferal fauna in Flensburg Fjord ranged from 15 to 223 ind. 10 cm^{-3}, on average 68 ind. 10 cm^{-3}. The abundance of dead specimens ranged from 16 to 454 tests 10 cm^{-3}, on average 127 tests 10 cm^{-3}. The assemblages consisted of six calcareous species: *Ammonia aomoriensis*, *Elphidium albiumbilicatum, Elphidium excavatum clavatum, Elphidium excavatum excavatum, Elphidium gerthi* and *Elphidium incertum*, and two arenaceous species *Ammotium cassis* and *Reophax dentaliniformis* (Fig. 9). Foraminiferal faunas were dominated by *A. aomoriensis*, *E. incertum* and *A. cassis* (Fig. 4). The specimens of common to rare species, which are not constantly represented in the foraminiferal assemblages, were combined to one group, called "Other" (Tables 5 and 6).

Living assemblages

Stations FF1 and FF5 showed a similar trend of population density and composition of living species during the seasonal cycle (Fig. 4). FF1 is located in the middle part of the fjord, where the sediment consists of sandy mud, whereas station FF5 is located in the outer fjord of Flensburg where muddy sand prevailed (Fig. 1). Maximum numbers of 101 and 129 ind. 10 cm^{-3} were observed in October at stations FF1 and FF5, when *A. aomoriensis* was frequent with 49 and 72 % (Fig. 4). At station FF1, *A. aomoriensis* was also frequent in April with 61 %, and it was common with 17 % in August. *Elphidium incertum* dominated with 52 and 48 % during summer, and *A. cassis* was rather rare with 1 % (Fig. 4). In contrast, *E. incertum* was the dominant species with 34 % on average during the whole year at station FF5 (Table 5). The arenaceous species *A. cassis* was very frequent in August and in February with 63 and 37 % (Table 5). At station FF4, which was also located in the outer Fjord, *E. incertum* was the dominant species during the whole year and showed a maximum of 94 % in April (Fig. 4). In comparison, *A. aomoriensis* was rare, ranging from 0 to 9 %. The data distribution suggests, that *A. cassis* immigrated in the community by October, and achieved maximum proportions of 36 % in December (Table 5).

Dead assemblages

During the whole investigation period, *A. aomoriensis* dominates the dead assemblages at stations FF1, FF4 and FF5 with 62 %, 46 % and 39 % on average (Fig. 4). At station FF1, abundance of dead foraminifera was consistently higher ranging from 118 to 454 tests 10 cm^{-3} in comparison to the other stations. At station FF1, *E. incertum* was common with 14 %, and *A. cassis* was very rare with 0.4 % on average throughout the year (Fig. 4). In contrast, *E. incertum* was common at stations FF4 and FF5, and depicted maximum values in February and April with 42 % on average at station FF4 (Table 6). The arenaceous species *A. cassis* was frequent with 50 % in June at station FF4, otherwise it was rare with 2 % on average at station FF5 (Table 6).

4.4 Co-variance of population density of living specimens

Living *A. aomoriensis* and *E. incertum* revealed mean population densities of 16 ind. 10 cm^{-3} and 33 ind. 10 cm^{-3}. No correlation with the sediment pore water pCO_2 was recognized (Fig. 5).

BGD
9, 7783–7830, 2012

In contrast to $p\text{CO}_2$, *A. aomoriensis* showed a co-variance with saturation state Ω_{calc}. Population density was comparatively low (5 ind. 10 cm^{-3}), when undersaturated conditions from 0.46 to 0.99 prevailed (Fig. 5). It was noticeable that station FF4 exhibited undersaturated conditions in sediment pore waters with an Ω_{calc} between 0.46 and 0.99 during the whole year, with the exception of October with Ω_{calc} of 1.76 (Table 4). During that time however, *A. aomoriensis* showed the lowest populations density of 3 ind. 10 cm^{-3} (Fig. 5, part A). By comparison, stations FF1 and FF5 were most of the time supersaturated for Ω_{calc} from 1.07 to 1.69 (Table 4), and revealed mean population densities of 19 ind. 10 cm^{-3} and 35 ind. 10 cm^{-3} (Fig. 5; part A).

In contrast, the population density of *E. incertum* showed no co-variance with sediment pore water Ω_{calc}. Under supersaturated Ω_{calc} conditions, the population density was lower with 15 ind. 10 cm^{-3}, in comparison to undersaturated values of Ω_{calc} with a population density of 53 ind. 10 cm^{-3} (Fig. 5; part C).

4.5 Tests of living calcareous foraminifera

The test walls of the dominant calcareous species *A. aomoriensis* and *E. incertum* were examined. Living *E. incertum* displayed no signs of dissolution. Occasionally, the last chambers of *E. incertum* were broken, which indicates impacts of mechanical forces, probably during sampling or processing (Fig. 6: 6).

64 % of the tests of living *A. aomoriensis* were intact and had a smooth surface, which was recognized in all samples during the one-year cycle (Fig. 9: 2). However, the remaining *A. aomoriensis* specimens showed different stages of tests, which were classified as: (1) intact tests (Fig. 9: 2), (2) loss of the last chamber (Fig. 6: 4) and (3) loss of more than two chambers (Fig. 6: 5). At station FF1 and FF5, 33 % and 29 % of *A. aomoriensis* specimens exhibited loss of the last chambers. The loss of more than two chambers was observed in 4 % and 13 % of the living specimens. Most of the dissolved chamber walls were heavily decalcified. They showed an irregular shape and

BGD
9, 7783–7830, 2012

were interrupted (Fig. 6: 1–3). At station FF4, all tests were destroyed and in nearly all individuals, only the inner organic lining was left in October and February.

Furthermore, some test walls of living *A. aomoriensis* exhibited recalcified structures (Fig. 6: 1–3). The newly formed chambers were usually characterized by test deformities such as an irregular shape (Fig. 6: 2–3). The walls of the chambers were not completely covered by a newly formed calcite lamella, which indicated a fragmentary precipitation of calcite from the external to the internal test walls (Fig. 6: 2). Old/compact and young/thinner chambers showed the same porosity (Fig. 6: 2).

5 Discussion

5.1 Carbonate chemistry in Flensburg Fjord

Whereas, the surface pCO_2 of Flensburg Fjord is close to the atmospheric CO_2 concentrations, bottom water conditions were much more variable during the seasonal cycle. This seasonal variability of the carbonate chemistry is also found elsewhere in near coastal marine systems (Borges and Frankignoulle, 1999; Borges et al., 2006; Provoost et al., 2010; Thomsen et al., 2010; Hofmann et al., 2011).

These natural fluctuations, due to seasonal stratification and respiration in deeper waters are common in eutrophicated coastal habitats and estuaries (Diaz and Rosenberg, 2008; Conley et al., 2009; Nikulina and Dullo, 2009; Thomsen et al., 2010; Melzner et al., 2012). Furthermore, sediment pore water carbonate chemistry, especially in the living benthic foraminiferal habitat from 0–1 cm, strongly deviated from the conditions in the bottom water. Sediment pore water exhibited perennial high pCO_2 values ranging from 1244 to 3324 µatm. The increase of pCO_2 is a consequence of the progressing oxygen depletion from the surface water to the anoxic sediments. In the near-surface sediment, the anaerobic bacterial decay of organic matter leads to production of metabolic bicarbonate (HCO_3^-) by nitrate and sulfate reduction (Yao and Millero, 1995). The end products, H_2S or N_2 are either degassing or are bound as iron

BGD
9, 7783–7830, 2012

sulphides. The gases are removed from the system and inhibit CO_2 dissociation and a lowering of pH (Kristensen et al., 1998; Brasse et al., 1999).

The A_T in the surface waters ranges from 1800 to 2100 µmol kg^{-1} and thereby is slightly lower than the buffer capacity of bottom water A_T (1800–2500 µmol kg^{-1}). However, the sediment pore water habitat of the benthic foraminifera exhibited a much higher alkalinity ranging from 2000 to 3500 µmol kg^{-1}. Remineralization products cause C_T and A_T enriched sediment pore waters and an enhanced CO_2 buffer capacity (Thomas et al., 2009). Consequently, Ω_{calc} of the sediment pore waters was much higher than in the water column for most time of the year. In contrast to station FF1 and FF5, Ω_{calc} of station FF4 was undersaturated during most time of the year. Both stations, FF4 and FF5, are located in Gelting Bay and have the same sediment, which is muddy sand. However, even slight differences in the sediment composition might cause different remineralization processes (Kristensen et al., 1998; Asmus et al., 1998a, b), which could explain the Ω_{calc} undersaturation at station FF4.

5.2 Foraminiferal community

The population density of the living assemblages showed fluctuations which can be attribute to the seasonality of food supply (Schönfeld and Numberger, 2007a). In particular, high values of food supply during April and October could mirror spring and autumn blooms. The subsequent flux of algal debris to the sea floor is the dominating parameter structuring the population density and species composition of benthic foraminiferal faunas (Altenbach, 1999; Morigi et al., 2001; Gooday, 2003). As such, it is conceivable that enhanced influx of organic matter provided sufficient food for a rich benthic community in Flensburg Fjord.

The composition of living and dead assemblages was not correlated with pCO_2. This infers that any shell loss of the dead assemblage due to dissolution in seasonal undersaturated sediment pore waters was instantly compensated by the delivery of empty tests from the living fauna through manifold reproduction.

BGD
9, 7783–7830, 2012

In this study, we observed that living *A. aomoriensis* was frequent in muddy sediments at the middle station FF1 of Flensburg Fjord during the entire period of investigation. Only in October 2009, *A. aomoriensis* was dominant in muddy sands at the outer Fjord station FF5. This occurrence peak was possibly related with favourable oxygen and saturation state conditions at this location in October. Also at the middle Fjord station FF1, the population density of *A. aomoriensis* varied apparently during the seasonal cycle, possibly in coherence with fluctuating oxygen conditions. On the other hand, station FF4 in southern Gelting Bay showed a noticeable low population density of *A. aomoriensis*. This part of Flensburg Fjord was reported as quiet area (Exon, 1971). Seasonal stratification and respiration in the deeper water causes hypoxic zones and unfavourable carbonate chemistry conditions, which could influence the survival and calcification of *A. aomoriensis*. The oxygen depletion could also promote the low *Ammonia* population densities at station FF4 (Alve and Nagy, 1986; Buzas-Stephens and Buzas, 2005; Polovodova and Schönfeld, 2008), even though sufficient food is available.

The low-oxic conditions would also explain the dominance of *E. incertum* living in the uppermost sediment layer during the whole year at station FF4. *Elphidium incertum* has been described as an intermediate-infaunal species, which dwells in the sediment down to 3–6 cm depth (Linke and Lutze, 1993). Under unfavorable oxygen conditions, this species moved in the uppermost sediment layers (Wefer, 1976). Furthermore, living *E. incertum* showed irregular spatial and temporal fluctuations in Flensburg Fjord. Higher population densities of *E. incertum* were observed in the middle Fjord station FF1 in June and in the outer Fjord station FF5 in April. The southern station FF4 in Gelting Bay, however, showed highest population densities of *E. incertum* in June and in April. Previous studies described, that the reproduction of *E. incertum* preferentially takes place after phytoplankton blooms, which deliver high amounts of suspended organic particles to the sediment surface (Altenbach, 1985; Gustafsson and Nordberg, 1999). Indeed, we observed a dense layer of filamentous algae covering the sediment surface at all stations in June 2009. This algal mat probably induced and sustained the

BGD
9, 7783–7830, 2012

dense population of *E. incertum* in June, whereas the high and even rising population density in April was caused by the late spring diatom bloom in 2010 (Smetacek, 1985; Schönfeld and Numberger, 2007b).

The arenaceous species *A. cassis* was only common in the central and open parts of the outer Flensburg Fjord, where muddy sand prevailed. A higher number of living *A. cassis* was observed in October and December at station FF4. This transient peak correlated with the highest salinity values of 22.3 and 24.1 recorded at this station. It has been detected that the ability of *A. cassis* to live in the SW Baltic Sea is controlled by salinity (Lutze, 1965). A rising salinity due to decadal, massive saltwater inflows from the Kattegat had led to increasing abundances of *A. cassis* in Kiel Bight during the following years (Schönfeld and Numberger, 2007a; Nikulina et al., 2008). A further important process which influenced the reproduction of *A. cassis* is the availability of food particles, in particular their enrichment at hydrographic boundary layers and at the sediment surface bathed by these internal nepheloid layers (Wefer, 1976; Olsson, 1976). Given these favorable conditions, *A. cassis* bloomed and dominated the foraminiferal assemblages in August at station FF5.

5.3 Comparison with earlier findings

Polovodova et al. (2009) described recent living foraminiferal distribution from Flensburg Fjord in June 2006. Three of the sampling stations were adjacent to our stations. The comparison revealed the changes in living faunal composition within three years (Fig. 7).

Our station FF1 was closely located to station PF16-19. They showed a similar species composition, 18 % *A. aomoriensis* and 57 % *E. incertum* in June 2006 and 15 % and 52 % in June 2009, respectively (Fig. 7). This similar species proportions revealed that the environmental setting did not change substantially between 2006 and 2009 at station FF1 in the middle Fjord.

Outer Fjord stations FF4 and FF5 are close to stations PF-16-21 and PF-16-26. They showed a distinct faunal change from June 2006 to 2009. In June 2006, *A. aomoriensis*

BGD
9, 7783–7830, 2012

was dominant with 70 % (station PF-16-21) and 94 % (station PF-16-26), whereas in 2009 *E. incertum* dominated with 78 % at station FF4 and was common at FF5 with 21 % (Fig. 7). Furthermore, a small population of *A. cassis* had re-immigrated before June 2009. This species comprised 6 % at station FF4 and 1 % at FF5.

On the one hand, this faunal change could reflect the year-to-year variability in parameters like salinity, food supply and oxygen content. The relationship with these parameters was documented for *A. beccarii*, *E. incertum* and *A. cassis* in previous studies (Wefer, 1976; Polovodova et al., 2009).

On the other hand, it is known that benthic foraminifera revealed irregular distribution pattern on the sea floor (Ellison, 1986; Schafer, 1973). The degree of patchiness varied, for instance a clumped distribution of many species reflects reproduction events (Buzas, 1968). Patchy colonization is a combination of many factors such as sediment composition (Bernstein et al., 1978; Bernstein and Meador, 1979) or microhabitat specialization (Jumars, 1975). Suggesting that the environmental factors influenced the distribution of species, patchiness of foraminiferal assemblages might play a certain role in the observed differences between June 2006 and 2009.

5.4 Response of living calcareous foraminifera to undersaturated Ω_{calc}

It is expected that foraminifera responds negatively to ocean acidification (Cigliano et al., 2010; Haynert et al., 2011). Laboratory studies revealed lowered calcification and decreased survival at elevated pCO_2 (Le Cadre et al., 2003; Kuroyanagi et al., 2009; Allison, 2010; Haynert et al., 2011; Fujita el al., 2011). In contrast, other laboratory studies showed no significant change of calcification under simulated future pCO_2 scenarios (Dissard et al., 2010; McIntyre-Wressnig et al., 2011).

To date, only a low number of field studies investigated the response of calcifying organisms in natural CO_2-rich habitats. At CO_2 vents off Ischia (Italy), settlement and overall abundance and species richness of benthic foraminifera was significantly decreased at the low pH site, which was undersaturated with respect to calcite (Cigliano et al., 2010; Dias et al., 2010). In contrast, calcareous benthic foraminifera from Flensburg

BGD
9, 7783–7830, 2012

are able to survive and continue calcification under high pCO_2values throughout the year. This infers no relationship between high pCO_2-levels and the calcification process itself.

Population density of living *A. aomoriensis*, one of the dominating calcifying species, co-varies with sediment pore water undersaturation of Ω_{calc}. This finding is in agreement with observations from the laboratory, where mean test diameter of *A. aomoriensis* decreases in treatments with $\Omega_{calc} < 1$, by up to 22 % (Haynert et al., 2011). Similarly, fitness and survival of the symbiont-bearing benthic foraminifera *Amphistegina gibbosa* and *Archaias angulatus* were not directly affected by elevated pCO_2 (McIntyre-Wressnig et al., 2011). These species were cultured at different pH levels of 8.12, 7.86 and 7.50 for six weeks. It is important to note that during the whole incubation time Ω_{calc} was supersaturated ranging from 5.4 to 1.5, even at a high pCO_2 of 2000 µatm ($\Omega_{calc} = 1.5$). This confirms our conclusion, that living foraminifera are adapted at high pCO_2 levels, but respond most sensitive to an undersaturation of Ω_{calc}.

In contrast, *Ammonia tepida* revealed the highest calcification and survival rates at undersaturated conditions ($\Omega < 1$) (Dissard et al., 2010). These results emphasize the need to understand the biological control of the calcification process in different foraminiferal species. Differences between Flensburg Fjord and Ischia might be explained by higher, slightly supersaturated Ω_{calc} values in the sediment of Flensburg Fjord, in contrast to the undersaturated conditions of the open water at Ischia. Nevertheless, the saturation state and not pCO_2 or pH seems to be the parameter which has the intense effect on calcification in benthic foraminifera. Therefore, it needs to be considered that foraminifera may not be subjected to undersaturation in sediments, which might cause a much lower vulnerability to increased atmospheric pCO_2 as observed in the Ischia study (Cigliano et al., 2010).

5.5 Test dissolution

Calcification is the process, which is expected to be highly affected by ocean acidification. Our study in Flensburg Fjord revealed no general impairment of calcification

BGD
9, 7783–7830, 2012

of living benthic foraminifera in a naturally CO_2-rich coastal environment. Only in undersaturated water, dissolution features were observed but the response was highly species specific. For instance, *E. incertum* does not exhibit any signs of dissolution, whereas *A. aomoriensis* shows different stages of test corrosion.

Similar dissolution features were observed in marginal marine foraminifera from several settings: Sandebukta, Nueces Bay, Flensburg Fjord and Cleveland Bay (Alve and Nagy, 1986; Buzas-Stephens and Buzas, 2005; Polovodova and Schönfeld, 2008), and on estuarine foraminifera from South Alligator River (Wang and Chappell, 2001). All these dissolution phenomena may have different background reasons inferred by anthropogenic or natural conditions (Le Cadre et al., 2003). Abrasion and predation were suggested by different authors as forces, which may act independently or amplify the foraminiferal shell loss (Bradshaw, 1957; Martin et al., 1995; Alve and Murray, 1999; Polovodova and Schönfeld, 2008). However, in a laboratory study with manipulated carbonate system induces similar stages of dissolution, which support the hypothesis that calcite undersaturation is the major reason of dissolution on tests of *A. aomoriensis*, also in Flensburg Fjord (Haynert et al., 2011).

In Flensburg Fjord, we observed recalcification structures on tests of *A. aomoriensis*, which is explained by seasonal fluctuations of Ω_{calc} in the sediment pore water. After periods of $\Omega_{calc} < 1$, *A. aomoriensis* are seemingly able to rebuild their shell when Ω_{calc} returns to a supersaturated state >1. The same has been observed on tests of *Ammonia beccarii*, which begin to recalcify when pH was increased after a period of low pH levels (Le Cadre et al., 2003). The recalcification begins between the septal walls or around protruding cytoplasmic masses. Such a "repair" commonly leads to development of morphological abnormalities (Stouff et al., 1999b; Le Cadre et al., 2000). Abnormal tests of foraminifera were also observed in Rio Una (Brazil), resulting from natural periodical acidification (Geslin et al., 2002).

In order to investigate, whether dissolution and recalcification had an influence on the growth of the specimens during their entire lifespan, we measured the size distribution in specimen of *A. aomorienis*. The diameter of living and dead *A. aomorienis*

BGD
9, 7783–7830, 2012

ranged from minimum 306 µm to maximum 461 µm, on average. Mean diameter of the dead assemblage ranged from minimum 269 µm to maximum 433 µm. The sizes of *A. aomorienis* are in good general agreement with populations from North Sea tidal flats (Hazeleger, 2010) in Quarternary sediments from the Dead Sea Rift, Israel (Almogi-Labin et al., 1995). Size distribution histograms differ between the successive sampling dates. Large proportions of small-sized tests or single modes indicating reproduction events (Swallow, 2000), which were increasing in size from one sampling event to another were not recognised. This can be regarded as corroborating evidence for generation times shorter than 88 days as reported by Bradshaw (1957, 1961). Thus infers that every *A. aomorienis* population has to be regarded individually in the context of the environmental factors that were prevailed at the particular station about a couple of weeks before sampling. Therefore certain foraminiferal species seem to cope much better with undersaturated conditions than other, which might lead to shifts in the community structure in future.

Test dissolution in foraminifera is also known from the geological record (Alve, 1995, 1999). *E. incertum* showed a higher resistance to undersaturation of Ω_{calc} in comparison to *A. aomoriensis*. Therefore, *A. aomoriensis* would be the better proxy for ocean acidification in the past. According to our results, calcification and recalcification of *A. aomoriensis* is a response to the environmental stress induced changes in Ω_{calc}. High proportions of corroded tests of *A. aomoriensis* in sediment cores could indicate variations in ecological parameters, in particular elevated environmental stress. Therefore both, morphological abnormalities and dissolution features could be useful proxies in paleoenvironmental reconstructions (Geslin et al., 2002).

5.6 Impact of rising atmospheric CO_2 on the carbonate chemistry of a coastal habitat

Future ocean acidification will amplify pCO$_2$ levels, especially in hypoxic water masses (Brewer and Pelzer, 2009; Melzner et al., 2012). Already today, low [CO_3^{2-}] are encountered in the habitat of Flensburg Fjord. Additional CO_2 will cause further increases of

BGD
9, 7783–7830, 2012

seawater pCO_2 and lowering of $[CO_3^{2-}]$ (Melzner et al., 2012). According to our calculations, additional CO_2 will also cause a strong increase of sediment pore water pCO_2 by about 1500 µatm to mean values of 3550 ± 780 µatm (Fig. 8). At the same time, pH and Ω_{calc} will decrease to mean values of 7.42 ± 0.08 and 0.59 ± 0.20 (Fig. 8). This would lead to a constant undersaturation of sediment pore water Ω_{calc} during the whole year cycle (Fig. 8).

In consequence of increasing atmospheric CO_2 concentrations, a much higher pCO_2 increase is expected for seasonal hypoxic habitats such as Flensburg Fjord compared to the global ocean. Elevated pCO_2 or low pH might not necessarily lead to a drastic change of the benthic foraminiferal community structure today. However certain species, in particular *A. aomoriensis* exhibited high sensitivity to present day undersaturated states already. In the future, more adverse conditions might lead to a strong decline in *A. aomoriensis* population density.

More tolerant calcareous species as *E. incertum* might dominate the benthic foraminiferal communities under future elevated pCO_2 conditions. This shift may eventually lead to changes in the benthic foraminiferal communities of Flensburg Fjord. The same will apply to other regions too, which are going to experience naturally undersaturated Ω_{calc} levels.

Furthermore, calcareous planktonic foraminifera in the water column might be more affect by the future pCO_2 increase in comparison to benthic foraminifera living in the surface sediments. They precipitate thinner test walls at reduced carbonate ion concentrations and higher atmospheric CO_2 levels (Spero et al., 1997; Bijma et al., 1999; Moy et al., 2009). The reduction of calcification of planktonic foraminifera may have a considerable impact on global carbonate production. At present, the foraminiferal fauna precipitate 0.2 Gt $CaCO_3$ per year on a global scale (Langer et al., 1997; Langer 2008), of which one-third is produced by planktonic foraminifers (Schiebel 2002). If their production will diminish, a shift from pelagic to neritic carbonate production is expected. The consequences for the global carbon budget are not yet foreseeable.

BGD
9, 7783–7830, 2012

6 Conclusions

The present study is based on dynamic analyses of the benthic foraminiferal assemblages in a naturally CO_2-rich coastal habitat of Flensburg Fjord. In this habitat, bottom and sediment pore water pCO_2 showed large seasonal fluctuations and sediment pore water pCO_2 is constantly high during the entire year. Nevertheless, the sediment pore water is slightly supersaturated with respect to calcite as consequence of higher alkalinity (A_T). This indicates that the benthic community is subjected to constantly high pCO_2.

The living and dead foraminiferal assemblages fluctuated seasonally and showed no relationship with sediment pore water pCO_2. Instead, the population density of the fauna showed individual fluctuations which can be attributed to the seasonality of food supply.

The population density of *A. aomoriensis*, one of the dominant calcifying species, covaries with sediment pore water undersaturation of Ω_{calc}. In contrast, the co-occurring calcareous species *E. incertum* showed no relationship to $\Omega < 1$. Also the dissolution response differs between the two species. *Elphidium incertum* displayed no signs of test dissolution, whereas *A. aomoriensis* showed different stages of shell loss. Test dissolution of *A. aomoriensis* could indicate environmental stress, such as undersaturation of Ω_{calc}. Therefore, dissolution features could be useful poxies in paleoenvironmental reconstructions.

The calculated future sediment pore water acidification in Flensburg Fjord is much higher than it is expected for the global ocean. We conclude that benthic foraminifera are relatively tolerant to current high pCO_2 conditions in Flensburg Fjord, which suggest that elevated pCO_2-levels do not lead to a drastic change in the foraminiferal communities. The modelled, future change of sediment pore water chemistry to low, undersaturated Ω_{calc}, however, might increase the mortality of the dominating species *A. aomoriensis*, which will ultimately lead to changes in benthic foraminiferal communities in Flensburg Fjord.

BGD

9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

Supplementary material related to this article is available online at: http://www.biogeosciences-discuss.net/9/7783/2012/bgd-9-7783-2012-supplement.pdf.

Acknowledgements. The authors are grateful to the crew of R/V Littorina for help with sampling. We acknowledge Sebastian Fessler (GEOMAR) and Arne Körtzinger (GEOMAR) for supporting the carbonate system measurements, Ute Schuldt (Institute of Geosciences, Kiel) and Mario Thöner (GEOMAR) for technical support on the Scanning Electronic Microscope. We also wish to thank Anna Nikulina (GEOMAR), who provided a map of the study area of Flensburg Fjord (SW Baltic Sea). We gratefully acknowledge the encouragement and advice of Frank Melzner (GEOMAR). This study was funded by the Excellence Cluster "Future Ocean" of Kiel University (grant no. CP 0801) and by the German Research Foundation (grant SCHO 605/7-1).

References

Allison, N., Austin, W., Paterson, D., and Austin, H.: Culture studies of the benthic foraminifera *Elphidium williamsoni:* Evaluating pH, Δ[CO32–] and inter-individual effects on test Mg/Ca, Chem. Geol., 274, 87–93, 2010.

Almogi-Labin, A., Siman-Tov, R., Rosenfeld, A., and Debard, E.: Occurrence and distribution of the foraminifer and *Ammonia beccarii tepida* (Cushman) in water bodies, Recent and Quaternary, of the Dead Sea Rift, Israel, Mar. Micropaleontol., 26, 153–159, 1995.

Altenbach, A. V.: Die Biomasse der benthischen Foraminiferen, Auswertungen von "Meteor"-Expeditionen im östlichen Nordatlantik, PhD-Thesis, CAU-Kiel, 167 pp., 1985.

Altenbach, A. V.: Scaling percentages and distributional patterns of benthic Foraminifera with flux rates of organic carbon, J. Foraminiferal. Res., 29, 173–185, 1999.

Alve, E.: Benthic foraminiferal distribution and recolonization of formerly anoxic environments in Dramrnensfjord, southern Norway, Mar Micropaleontol, 25, 169–186, 1995.

Alve, E.: Colonization of new habitats by benthic foraminifera: a review, Earth-Sci. Rev., 46, 167–185, 1999.

BGD

9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

Alve, E. and Nagy, J.: Estuarine foraminiferal distribution in Sandebukta, a branch of the Oslo Fjord, J. Foraminiferal. Res., 16, 261–284, 1986.
Alve, E. and Murray, J. W.: Marginal marine environments of the Skagerrak and Kattegat: a baseline study of living (stained) benthic foraminifera, Palaeogeogr. Palaeocl., 146, 171–193, 1999.
Asmus, R., Jensen, M. H., Murphy, D., and Doerffer, R.: Primary production of microphytobenthos, phytoplankton, and the annual yield of macrophytic biomass in the Sylt Rømø Wadden Sea, in:Ökosystem Wattenmeer: Austausch, Transport und Stoffwandlungsprozesse, edited by: Gätje, C. and Reise, K., Springer, Berlin, 367–391, 1998a.
Asmus, H., Lackschewitz, D., Asmus, R., Scheiffarth, G., Nehls, G., and Herrmann, J. P.: Carbon flow in the food web of tidal flats in the Sylt–Rømø Bight, In: Gätje, C., Reise, K. (Eds.), Ökosystem Wattenmeer: Austausch, Transport und Stoffwandlungsprozesse, Springer, Berlin, 393–420, 1998b.
Bernstein, B. B. and Meador, J. P.: Temporal persistence of biological patch structure in an abyssal benthic community, Mar. Biol., 51, 179–183, 1979.
Bernstein, B. B., Hessler, R. R., Smith, R., and Jumars, P. A.: Spatial dispersion of benthic Foraminifera in the abyssal central North Pacific, Limnol. Oceanogr., 23, 401–416, 1978.
Bijma, J., Spero, H. J., and Lea, D. W.: Reassessing foraminiferal stable isotope geochemistry: impact of the oceanic carbonate system (experimental results), in: Use of proxies in paleoceanography: examples from the South Atlantic, edited by: Fisher, G. and Wefer, G., Springer, Heidelberg, 489–512, 1999.
Borges, A. V., Schiettecatte, L. S., Abril, G., Delille, B., and Gazeau, F.: Carbon dioxide in European coastal waters, Estuar. Coast. Shelf. S., 70, 375–387, 2006.
Borges, A. V. and Frankignoulle, M.: Daily and seasonal variations of the partial pressure of CO_2in surface seawater along Belgian and southern Dutch coastal areas, J. Mar. Syst., 19, 251–266, 1999.
Borges, A. V. and Gypens, N.: Carbonate chemistry in the coastal zone responds more strongly to eutrophication than ocean acidification, Limnol. Oceanogr., 55, 346–353, 2010.
Bradshaw, J.: Laboratory studies on the rate of growth of the foraminifer *Streblus beccarri* (Linne) var. *tepida* (Cushman), J. Paleontology, 31, 1138–1147, 1957.
Bradshaw, J.: Laboratory experiments on the ecology of foraminifera, Contrib. Cushman Found. Foraminifer Res., 7, 95–107, 1961.

BGD
9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

Brasse, S., Reimer, A., Seifert, R., and Michaelis, W.: The influence of intertidal mudflats on the dissolved inorganic carbon and total alkalinity distribution in the German Bight, southeastern North Sea, J. Sea. Res., 42, 93–103, 1999.

Brewer, P. G. and Peltzer, E. T.: Limits to marine life, Science, 324, 347–348, 2009.

Buzas, M. A.: On the spatial distribution of foraminifera, Contrib. Cushman Found. Foraminifer Res, 19, 411–422, 1968.

Buzas-Stephens, P. and Buzas, M. A.: Population dynamics and dissolution of Foraminifera in Nuices Bay, Texas, J. Foraminiferal. Res., 35, 248–258, 2005.

Caldeira, K. and Wickett, M. E.: Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean, J. Geophys. Res., 110, C09S04, doi:10.1029/2004JC002671, 2005.

Cigliano, M., Gambi, M. C., Rodolfo-Metalpa, R., Patti, F. P., and Hall-Spencer, J. M.: Effects of ocean acidification on invertebrate settlement at volcanic CO_2 vents, Mar. Biol., doi:10.1007/s00227-010-1513-6, 2010.

Conley, D. J., Björck, S., Bonsdorff, E., Carstensen, J., Destouni, G., Gustafsson, B. G., Hietanen, S., Kortekaas, M., Kuosa, H., Meier, M. H. E., Müller-Karulis, B., Nordeberg, K., Norkko, A., Nürnberg, G., Pitkänen, H., Rabalais, N. N., Rosenberg, R., Savchuck, O. P., Slomp, C. P., Voss, M., Wulff, F., and Zillen, L.: Hypoxia-related processes in the Baltic, Sea Environ. Sci. Technol., 43, 3412–3420, 2009.

Dias, B. B., Hart, M. B., Smart, C. W., and Hall-Spencer, J. M.: Modern seawater acidification: the response of foraminifers to high-CO_2 conditions in the Mediterranean Sea, J. Geol. Soc., 167, 10050, doi:10.1144/0016-76492010-050, 2010.

Diaz, R. J. and Rosenberg, R.: Spreading dead zones and consequences for marine ecosystems, Science, 321, 926–929, 2008.

Dickson, A. G. and Millero, F. J.: A comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media, Deep-Sea Res. A, 34, 1733–1743, 1987.

Dickson, A. G.: Standard potential of the reaction–$AgCl_S$ + $^1/_2$ H_2 = Ag_S ? HCl_{Aq} and the standard acidity constant of the ion HSO_4^- in synthetic sea-water from 273.15-K to 318.15-K, J. Chem. Thermodyn., 22, 113–127, 1990.

Dickson, A. G., Afghan, J. D., and Anderson, G. C.: Reference materials for oceanic CO_2 analysis: a method for the certification of total alkalinity, Mar. Chem., 80, 185–197, 2003.

Dickson, A. G., Sabine, C. L., and Christian, J. R.: Guide to best Practices for Ocean CO_2 Measurements, PICES Special Publications, 191 pp., 2007.

Dissard, D., Nehrke, G., Reichart, G. J., and Bijma, J.: Impact of seawater pCO2 on calcification and Mg/Ca and Sr/Ca ratios in benthic foraminifera calcite: results from culturing experiments with *Ammonia tepida*, Biogeosciences, 7, 81–93, doi:10.5194/bg-7-81-2010, 2010.
Ellison, R., Broome, R., and Ogilvie, R.: Foraminiferal response to trace metal contamination in the Patapsco River and Baltimore Harbour, Maryland, Mar. Pollut. Bull., 17, 419–423, 1986.
Erez, J.: The source of ions for biomineralization in foraminifera and their implications for paleoceanographic proxies, Rev. Mineral. Geochem., 54, 115–149, 2003.
Exon, N.: Holocene sedimentation in and near the outer Flensburg Fjord (westernmost Baltic Sea), PhD-thesis, CAU Kiel, 102 pp., 1971.
Exon, N.: Sedimentation in the outer Flensburg Fjord area (Baltic Sea) since the last Glaciation, Meyniana, 22, 5–6, 1972.
Fabricius, K. E., Langdon, C., Uthicke, S., Humphrey, C., Noonan, S., De'ath, G., Okazaki, R., Muehllehner, N., Glas, M. S., and Lough, J. M.: Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations, Nature Clim., 1, 165–169, 2011.
Feely, R. A., Sabine, C. L., Lee, K., Berelson, W., Kleypas, J., Fabry, V. J., and Millero, F. J.: Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans, Science, 305, 362–366, 2004.
Fisher, R. A., Corbet, A. S., and Williams, C. B.: The relation between the number of species and the number of individuals in a random sample of an animal population, J. Anim. Ecol., 12, 42–58, 1943.
Frenzel, P., Tech, T., and Bartholdy, J.: Checklist and annotated bibliography of Recent Foraminiferida from the German Baltic Sea coast, in: Methods and applications in micropaleontology, edited by: Tyszka, J., Stud. Geol. Pol., 124, 67–86, 2005.
Fujita, K., Hikami, M., Suzuki, A., Kuroyanagi, A., Sakai, K., Kawahata, H., and Nojiri, Y.: Effects of ocean acidification on calcification of symbiont-bearing reef foraminifers, Biogeosciences, 8, 2089–2098, doi:10.5194/bg-8-2089-2011, 2011.
Gattuso, J.-P., Frankignoulle, M., Bourge, I., Romaine, S., and Buddemeier, R. W.: Effect of calcium carbonate saturation of seawater in coral calcification, Glob. Planet. Change 18, 37–46, 1998.
Geslin, E., Debenay, J. P., Duleba, W., and Bonetti, C.: Morphological abnormalities of foraminiferal tests in Brazilian environments: comparison between polluted and nonpolluted areas, Mar. Micropaleontol., 45, 151–168, 2002.

BGD
9, 7783–7830, 2012
The benthic foraminiferal community
K. Haynert et al.

Gooday, A. J.: Benthic foraminifera (protista) as tools in deep-water palaeoceanography: Environmental influences on faunal characteristics, Mar. Biol., 46, 1–90, 2003.
Grobe, H. and Fütterer, D.: Zur Fragmentierung benthischer Foraminiferen in der Kieler Bucht (Westliche Ostsee), Meyniana, 33, 85–96, 1981.
Gustafsson, M. and Nordberg, K.: Benthic foraminifera and their response to hydrography, periodic hypoxic conditions and primary production in the Koljö fjord on the Swedish west coast, J. Sea. Res., 41, 163–178, 1999.
Hall-Spencer, J. M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner S. M., Rowley, S. J., Tedesco, D., and Buia, M.-C.: Volcanic carbon dioxide vents show ecosystem effects of ocean acidification, Nature 454, 96–99, 2008.
Haynert, K., Schönfeld, J., Riebesell, U., and Polovodova, I.: Biometry and dissolution features of the benthic foraminifer *Ammonia aomoriensis* at high pCO_2, Mar. Ecol. Prog. Ser., 432, 53–67, 2011.
Hazeleger, J. H.: In situ foraminifera food dynamics on an intertidal mudflat after a severe induced hypoxia Western Scheldt, Netherlands, Faculty of Geosciences Theses, Univeristy Utecht, 2010.
Hofmann, G. E., Smith, J. E., Johnson, K. S., Send, U., Levin, L. A., Micheli, F., Paytan, A., Price, N. N., Peterson, B., Takeshita, Y., Matson, P. G., Crook, E. D., Kroeker, K. J., Gambi, M. C., Rivest, E. B., Frieder, C. A., Yu, P. C., and Martz, T. R.: High-frequency dynamics of ocean pH: a multi-ecosystem comparison, PLos ONE, 6, e28983, 2011.
Ivanenkov, V. N. and Lyakhin, Y. I.: Determination of total alkalinity in seawater, in: Methods of Hydrochemical Investigations in the Ocean, edited by: Borodovsky, O. K. and Ivanenkov, V. N., Nauka, Moscow, 110–114, 1978.
Jumars, P. A.: Environmental grain and polychaete species' diversity in a bathyal benthic community, Mar. Biol. ,30, 253–266, 1975.
Kleypas, J. A., Buddemeier, R. W., Archer, D., Gattuso, J. P., Langdon, C., and Opdyke, B. N.: Geochemical consequences of increased atmospheric CO_2 on coral reefs, Science, 284, 118–120, 1999.
Kristensen, E., Jensen, M. H., and Jensen, K. M.: Sulfur dynamics in sediments of Königshafen, in: Ökosystem Wattenmeer: Austausch, Transport und Stoffwandlungsprozesse, edited by: Gätje, C. and Reise, K., Springer, Berlin, 233–256, 1998.

Kuroyanagi, A., Kawahata, H., Suzuki, A., Fujita, K., and Irie, T.: Impacts of ocean acidification on large benthic foraminifers: results from laboratory experiments, Mar. Micropaleontol., 73, 190–195, 2009.
Langer, M. R., Silk, M. T., and Lipps, J. H.: Global ocean carbonate and carbon dioxide production: the role of reef foraminifera, J. Foraminiferal. Res., 27, 271–277, 1997.
Langer, M. R.: Assessing the contribution of foraminiferan protists to global ocean carbonate production, J. Eukaryot. Microbiol., 55, 163–169, 2008.
Le Cadre, V., Debenay, J. P., and Lesourd, M.: Low pH effects on test deformation: implications for studying test deformations as a pollution indicator, In: The Second International Conference on Application of Micro- and Microorganisms to Environmental Problems, Winnipeg, Canada, 74 pp., 2000.
Le Cadre, V., Debenay, J. P., and Lesourd, M.: Low pH effects on *Ammonia beccarii* test deformation: implications for using test deformations as a pollution indicator, J. Foraminiferal. Res., 33, 1–9, 2003.
Lewis, E. and Wallace, D. W. R.: Program developed for CO_2 system calculations, Oak Ridge, Oak Ridge National Laboratory ORNL/CDIAC, 105, 1998.
Linke, P. and Luze, G. F.: Microhabitat preferences of benthic foraminifera – a static concept or a dynamic adaptation to optimize food acquisition?, Mar. Micropaleontol., 20, 215–234, 1993.
Lutze, G. F.: Zur Foraminiferen-Fauna der Ostsee, Meyniana, 15, 75–142, 1965.
Lutze, G. F.: Foraminiferen der Kieler Bucht (Westliche Ostsee): 1 'Hausgartengebiet' des Sondersforchungsbereiches 95 der Universität Kiel, Meyniana, 26, 9–22, 1974.
Lutze, G. F. and Altenbach, A.: Technik und Signifikanz der Lebendfärbung benthischer Foraminiferen mit Bengalrot, Geologisches Jahrbuch, A 128, 251–265, 1991.
Martin, R. E., Harris, M. S., and Liddell, W. D.: Taphonomy and time-averaging of foraminiferal assemblages in Holocene tidal flat sediments, Bahia la Choya, Sonora, Mexico (northern Gulf of California), Mar. Micropaleontol., 26, 187–206, 1995.
McIntyre-Wressnig, A., Bernhard, J. M., McCorkle, D. C., and Hallock, P.: Non-lethal effects of ocean acidification on two symbiont-bearing benthic foraminiferal species, Biogeosciences Discuss., 8, 9165–9200, doi:10.5194/bgd-8-9165-2011, 2011.
Mehrbach, C., Culberso, C. H., Hawley, J. E., and Pytkowic, R. W.: Measurement of the apparent dissociation-constants of carbonic acid in seawater at atmospheric-pressure, Limnol. Oceanogr., 18, 897–907, 1973.

Melzner, F., Thomsen, J., Koeve, W., Oschlies, A., Gutowska, M. A., Bange, H. W., Hansen, H. P., and Körtzinger, A.: Future ocean acidification will be amplified by hypoxia in coastal habitats, press, doi:10.1007/s00227-012-1954-1, Mar. Biol., 2012.
Mintrop, L., Perez, F. F., Gonzalez-Davila, M., Santana-Casiano, M. J., and Körtzinger, A.: Alkalinity determination by potentiometry: Intercalibration using three different methods, Cienc. Mar., 26, 23–37, 2000.
Morigi, C., Jorissen, F. J., Gervais, A., Guichard, S., and Borsetti, A. M.: Benthic foraminiferal faunas in surface sediments off NW Africa: relationship with the organic flux to the ocean floor, J. Foraminiferal. Res., 31, 350–368, 2001.
Moy, A. D., Howard, W. R., Bray, S. G., and Trull, T. W.: Reduced calcification in modern Southern Ocean planktonic foraminifera, Nat. Geosci., 2, 276–280, 2009.
Nikulina, A., Polovodova, I., and Schönfeld, J.: Foraminiferal response to environmental changes in Kiel Fjord, SW Baltic Sea, Earth (Waukesha), 3, 37–49, 2008.
Nikulina, A. and Dullo, W. C.: Eutrophication and heavy metal pollution in the Flensburg Fjord: a reassessment after 30 years, Mar. Pollut. Bull., 58, 905–915, 2009.
Olsson, I.: Distribution and ecology of foraminiferan *Ammotium cassis* (Parker) in some Swedish estuaries, Zoon, 4, 137–147, 1976.
Otto, G. H.: Comparative tests of several methods of sampling heavy mineral concentrates, J. Sediment. Petrol., 3, 30–39, 1933.
Polovodova, I. and Schönfeld, J.: Foraminiferal test abnormalities in the western Baltic Sea, J. Foraminiferal. Res., 38, 318–336, 2008.
Polovodova, I., Nikulina, A., Schönfeld, J., and Dullo, W. C.: Recent benthic foraminifera in the Flensburg Fjord, J. Micropaleontol., 28, 131–142, 2009.
Provoost, P., van Heuven, S., Soetaert, K., Laane, R. W. P. M., and Middelburg, J. J.: Seasonal and long-term changes in pH in the Dutch coastal zone, Biogeosciences, 7, 3869–3878, doi:10.5194/bg-7-3869-2010, 2010.
Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., Shepherd, J., Turley, C., and Watson, A.: Ocean acidification due to increasing atmospheric carbon dioxide. The Royal Society policy document 12/05, The Clyvedon Press Ltd, Cardiff, 2005.
Riebesell, U., Zondervan, I., Rost, B., Tortell, P. D., Richard, E. Z., and Morel, F. M. M.: Reduced calcification of marine plankton in response to increased atmospheric CO_2, Nature, 407, 364–367, 2000.

BGD
9, 7783–7830, 2012

Rottgardt, D.: Mikropaläontolgische wichtige Bestandteile rezenter brackischer Sedimente an den Küsten Schleswig-Holsteins, Meyniana, 1, 169–228, 1952.
Schafer, C. T.: Distribution of foraminifera near pollution sources in Chaleur Bay, Water Air Soil Poll., 2, 219–233, 1973.
Schiebel, R.: Planktic foraminiferal sedimentation and the marine calcite budget, Global Biogeochem. Cy., 16, 1065, doi:10.1029/2001GB001459, 2002.
Schönfeld, J. and Numberger, L.: Seasonal dynamics and decadal changes of benthic foraminiferal assemblages in the western Baltic (NW Europe), J. Micropaleontol., 26, 47–60, 2007a.
Schönfeld, J. and Numberger, L.: The benthic foraminiferal response to the 2004 spring bloom in the western Baltic Sea, Mar. Micropaleontol., 65, 78–95, 2007b.
Shannon, C. E.: A mathematical theory of communication, At and T Tech J., ACM SIGMOBILE Mobile Computing and Communications Review, doi:10.1145/584091.584093, 27, 379–423, 1948a.
Shannon, C. E.: A mathematical theory of communication, At and T Tech J, ACM SIGMOBILE Mobile Computing and Communications Review, 27, 379–423, 1948b.
Smetacek, V.: The annual cycle of Kiel Bight Plankton: a long-term analysis, Estuaries, 8, 145–157, 1985.
Spero, H. J., Bijma, J., Lee, D. W., and Bemis, B. E.: Effect of seawater carbonate concentration on foraminiferal carbon and oxygen isotopes, Nature, 390, 497–500, 1997.
Stouff, V., Geslin, E., Debenay, J. P., and Lesourd, M.: Origin of morphological abnormalities in *Ammonia*(Foraminifera): studies in laboratory and natural environments, J. Foraminiferal. Res., 29, 152–170, 1999b.
Swallow, J. E.: Intra-annual variability and patchiness in living assemblages of salt-marsh foraminifera from Mill Rythe Creek, Chichester Harbour, England, J. Micropaleontol., 19, 9–22, 2000.
Thomas, H., Schiettecatte, L.-S., Suykens, K., Koné, Y. J. M., Shadwick, E. H., Prowe, A. E. F., Bozec, Y., de Baar, H. J. W., and Borges, A. V.: Enhanced ocean carbon storage from anaerobic alkalinity generation in coastal sediments, Biogeosciences, 6, 267–274, doi:10.5194/bg-6-267-2009, 2009.
Thomsen, J., Gutowska, M. A., Saphörster, J., Heinemann, A., Trübenbach, K., Fietzke, J., Hiebenthal, C., Eisenhauer, A., Körtzinger, A., Wahl, M., and Melzner, F.: Calcifying inverte-

BGD
9, 7783–7830, 2012

brates succeed in a naturally CO2-rich coastal habitat but are threatened by high levels of future acidification, Biogeosciences, 7, 3879–3891, doi:10.5194/bg-7-3879-2010, 2010.
Wang, P. and Chappell, J.: Foraminifera as Holocene environmental indicators in the South Alligator River, northern Australia, Quat. Int., 83–85, 47–62, 2001.
Wefer, G.: Umwelt, Produktion und Sedimentation benthischer Foraminiferen in der westlichen Ostsee, Reports Sonderforschungsbereich 95 Wechselwirkung Meer-Meeresboden, 14, 1–103, 1976.
Yao, W. and Millero, F. J.: The Chemistry of the Anoxic Waters in the Framvaren Fjord, Norway, Aquat Geochem, 1, 53–88, 1995.
Zeebe, R. E. and Wolf-Gladrow, D.: CO_2 in seawater: equilibrium, kinetics, isotopes, in: Elsevier oceanography series, edited by: Halpern, D., Series 65, Elsevier, Amsterdam, 2001.

BGD
9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

Table 1. Description of the sampling stations in Flensburg Fjord: specification, device, latitude and longitude, water depth in meter, and sediment type at the corer stations (FF1, FF4 and FF5).

Stations	Specification	Device	Latitude [N]	Longitude [E]	Depth [m]	Sediment type
FF1	Corer station	MUC	54°50.50′	9°37.00′	13	sandy mud
PF16-19 (Polovodova, 2008)	Corer station	Rumohr corer	54°50.20′	9°36.84′	10	sandy mud
FF2	Water chemistry station	CTD	54°49.00′	9°43.00′	18	–
FF3	Water chemistry station	CTD	54°50.00′	9°50.00′	27	–
FF4	Corer station	MUC	54°47.02′	9°51.37′	13	muddy sand
PF16-21 (Polovodova, 2008)	Corer station	Rumohr corer	54°46.92′	9°51.26′	9	muddy sand
FF5	Corer station	MUC	54°48.02′	9°53.05′	13	muddy sand
PF16-26 (Polovodova, 2008)	Corer station	Rumohr corer	54°48.28′	9°53.49′	8	muddy sand
FF6	Water chemistry station	CTD	54°47.00′	10°00.00′	22	–
FF7	Water chemistry station	CTD	54°46.00′	10°10.00′	23	–

BGD
9, 7783–7830, 2012

Table 2. Flensburg Fjord surface seawater chemistry speciation 2009 to 2010 at the sampling stations (FF1-FF7). Temperature and salinity were recorded using a CTD48M probe. Analyses for total alkalinity (A_T) and dissolved inorganic carbon (C_T) were measured by coulometric and potentiometric titration using SOMMA and VINDTA systems. pH_{NBS}, carbon dioxide partial pressure (pCO_2) and omega of calcite (Ω_{calc}) were calculated using the CO2Sys-software.

Surface water							
Station	Temperature [°C]	Salinity	pH_{NBS}	A_T [μmol kg^{-1}]	C_T [μmol kg^{-1}]	pCO_2 [μatm]	Ω_{calc}
FF1 (1 m)							
02.06.2009	16.0	15.8	8.24	1933.3	1820.3	368	2.62
18.08.2009	17.7	18.6	8.05	1973.8	1891.6	585	2.05
20.10.2009	10.3	21.1	8.10	2056.8	1975.0	492	1.93
07.12.2009	6.7	17.3	8.09	1972.9	1923.8	499	1.45
15.02.2010							
19.04.2010	7.6	15.7	8.06	1900.4	1862.4	532	1.30
FF2 (1 m)							
02.06.2009	15.9	15.6	8.23	1918.5	1810.0	375	2.54
18.08.2009	17.8	18.6	8.19	1988.2	1862.7	410	2.78
20.10.2009	10.9	20.8	8.03	2038.0	1972.4	575	1.70
07.12.2009	6.8	17.4	8.08	1980.3	1932.0	509	1.44
15.02.2010	−0.8	17.2	7.66	1904.8	1972.0	1249	0.40
19.04.2010	7.8	15.2	8.20	1889.1	1822.2	380	1.72
FF3 (1 m)							
02.06.2009	16.3	15.4	8.21	1907.0	1805.4	398	2.42
18.08.2009	18.2	18.1	8.27	1976.8	1826.6	336	3.24
20.10.2009	10.7	20.7	8.10	2030.8	1948.1	484	1.93
07.12.2009	7.9	18.4	8.03	1982.4	1939.2	577	1.37
15.02.2010	−0.9	17.1	8.23	1952.5	1897.5	325	1.46
19.04.2010	7.4	15.0	8.30	1890.2	1800.5	294	2.10
FF4 (1 m)							
02.06.2009							
18.08.2009							
20.10.2009							
07.12.2009	7.8	18.6	8.03	1980.3	1936.5	576	1.37
15.02.2010	−0.8	17.1	7.78	1912.0	1950.6	941	0.53
19.04.2010	8.0	14.3	8.34	1882.2	1784.0	271	2.27
FF5 (1 m)							
02.06.2009							
18.08.2009							
20.10.2009	10.7	20.7	8.09	2032.0	1954.2	502	1.88
07.12.2009	8.0	18.6	7.99	1980.0	1943.0	622	1.29
15.02.2010	−0.8	17.1	7.85	1949.6	1974.7	820	0.62
19.04.2010	7.3	14.9	8.22	1874.8	1805.0	355	1.76
FF6 (1 m)							
02.06.2009	15.6	15.0	8.21	1881.6	1785.2	392	2.32
18.08.2009	18.6	17.0	8.29	1934.9	1787.9	325	3.23
20.10.2009							
07.12.2009	7.9	19.0	8.08	1993.5	1935.5	507	1.57
15.02.2010	−0.8	16.8	8.25	1936.4	1877.9	307	1.50
19.04.2010	6.7	13.3	8.32	1830.2	1749.3	281	1.96
FF7 (1 m)							
02.06.2009	14.5	15.1	8.22	1890.9	1796.0	385	2.28
18.08.2009	20.0	15.9	8.25	1893.9	1762.5	361	3.00
20.10.2009	10.8	19.9	8.23	1957.8	1845.9	346	2.37
07.12.2009	7.0	17.2	8.16	1926.1	1860.7	408	1.66
15.02.2010	−0.9	16.2	8.05	1903.7	1889.0	495	0.94
19.04.2010	6.7	13.9	8.12	1821.0	1781.7	455	1.29

BGD
9, 7783–7830, 2012

Table 3. Water chemistry parameters of the near-bottom water (1 m above the sea floor) at stations FF2, FF3, FF6 and FF7 and of the bottom water (1 cm above the sediment surface) at stations FF1, FF4 and FF5 from June 2009 to April 2010. Temperature and salinity were measured by CTD48M probe at all stations from FF1 to FF7. At stations FF1, FF4 and FF5, the bottom water pH_{NBS} were measured using a WTW 340i. Analysis of total alkalinity (A_T) was determined with a Metrohm titration instrument. Dissolved inorganic carbon (C_T), carbon dioxide partial pressure (pCO_2), and omega calcite (Ω_{calc}) were calculated using the CO2Sys-program. At stations FF2, FF3, FF6 and FF7, analyses for total alkalinity (A_T) and dissolved inorganic carbon (C_T) were measured by coulometric and potentiometric titration using SOMMA and VINDTA systems. pH_{NBS}, carbon dioxide partial pressure (pCO_2) and omega of calcite (Ω_{calc}) were calculated using the CO2Sys-software.

Near-bottom and bottom water							
Station	Temperature [°C]	Salinity	pH_{NBS}	A_T [μmol kg^{-1}]	C_T [μmol kg^{-1}]	pCO_2 [μatm]	Ω_{calc}
Bottom water FF1 (13 m)							
02.06.2009	13.2	19.9	7.63	2388.4	2385.6	1337	1.19
18.08.2009	14.6	20.0	7.54	2199.5	2213.7	1536	0.95
20.10.2009	10.5	21.0	7.29	2465.7	2581.7	3074	0.53
07.12.2009	9.1	21.5	7.84	2174.0	2126.6	700	1.51
15.02.2010							
19.04.2010	5.7	18.7	7.86	2353.5	2322.2	739	1.41
Near-bottom water FF2 (18 m)							
02.06.2009	7.2	21.2	7.86	2060.1	2046.6	857	1.04
18.08.2009	11.6	21.6	7.40	2079.7	2173.1	2661	0.45
20.10.2009	11.0	21.4	7.93	2073.6	2030.7	754	1.40
07.12.2009	9.2	23.0	7.98	2053.7	1998.2	631	1.52
15.02.2010	−0.8	17.2	8.03	1951.5	1938.3	529	0.94
19.04.2010	4.3	19.4	8.03	2023.9	1987.5	557	1.26
Near-bottom water FF3 (27m)							
02.06.2009	7.4	23.5	7.92	2123.3	2085.1	735	1.32
18.08.2009	11.1	23.4	7.45	2117.9	2193.1	2348	0.53
20.10.2009	13.2	23.4	7.49	2093.6	2149.8	2168	0.61
07.12.2009	9.0	24.0	8.02	2076.3	2006.2	568	1.70
15.02.2010	−0.2	17.5	8.08	1985.8	1958.9	478	1.11
19.04.2010	2.7	22.4	7.55	2022.4	2095.3	1631	0.45
Bottom water FF4 (13m)							
02.06.2009	15.1	20.4	7.52	2367.3	2350.3	1267	1.34
18.08.2009	12.8	21.1	7.43	2236.1	2283.7	1982	0.72
20.10.2009	11.2	22.4	7.21	2360.4	2491.4	3429	0.45
07.12.2009	8.6	24.1	7.85	2187.8	2131.2	673	1.60
15.02.2010	−0.4	16.8	7.81	1816.8	1823.3	634	0.70
19.04.2010	4.8	19.0	7.88	2234.5	2201.5	655	1.35

BGD
9, 7783–7830, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 3. Continued.

Near-bottom and bottom water							
Station	Temperature [°C]	Salinity	pH_{NBS}	A_T [μmol kg^{-1}]	C_T [μmol kg^{-1}]	pCO_2 [μatm]	Ω_{calc}
Bottom water FF5 (13 m)							
02.06.2009	10.3	20.2	7.83	2125.5	2082.8	727	1.45
18.08.2009	15.3	19.8	7.47	2239.1	2270.8	1861	0.85
20.10.2009	11.9	21.6	7.29	2465.7	2573.0	3083	0.57
07.12.2009	8.8	20.9	7.81	2174.0	2138.9	769	1.36
15.02.2010	−0.4	16.9	7.94	1804.6	1784.3	465	0.98
19.04.2010	5.6	18.8	7.94	2374.9	2321.6	604	1.70
Near-bottom water FF6 (22 m)							
02.06.2009	7.6	22.0	7.87	2070.3	2051.0	843	1.10
18.08.2009	11.2	23.8	7.50	2115.9	2175.3	2091	0.59
20.10.2009							
07.12.2009	9.0	23.5	8.01	2056.1	1992.4	585	1.62
15.02.2010	−0.8	17.2	8.19	1960.1	1913.6	362	1.34
19.04.2010	2.9	21.4	7.68	2038.9	2081.0	1248	0.59
Near-bottom water FF7 (23m)							
02.06.2009	8.7	26.3	7.87	2082.3	2043.1	796	1.30
18.08.2009	11.9	22.9	7.46	2089.3	2161.3	2326	0.53
20.10.2009	13.4	24.7	8.00	1985.0	1904.1	588	1.84
07.12.2009	9.0	22.9	8.02	2050.6	1986.8	577	1.62
15.02.2010	1.1	18.6	7.96	1974.5	1964.2	624	0.93
19.04.2010	2.9	22.8	7.63	2072.0	2122.5	1379	0.56

BGD
9, 7783–7830, 2012

Table 4. Seawater carbonate chemistry of bottom water (1 cm above the sediment surface) and sediment sediment pore water (0-1 cm) at stations FF1, FF4 and FF5 during the one year cycle. Bottom and sediment pore water pH_{NBS}were measured using a WTW 340i. Total alkalinity (A_T) was determined with a Metrohm titration instrument. Dissolved inorganic carbon (C_T), carbon dioxide partial pressure (pCO_2), and omega calcite (Ω_{calc}) were calculated using the CO2Sys-software.

	bottom water	sediment pore water 0–1 cm	bottom water	sediment pore water 0–1 cm	bottom water	sediment pore water 0–1 cm	bottom water	sediment pore water 0–1 cm	bottom water	sediment pore water 0–1 cm
Station	pH_{NBS}	pH_{NBS}	A_T [μmol kg^{-1}]	A_T [μmol kg^{-1}]	C_T [μmol kg^{-1}]	C_T [μmol kg^{-1}]	pCO_2 [μatm]	pCO_2 [μatm]	Ω_{calc}	Ω_{calc}
FF1										
02.06.2009	7.63	7.52	2388.4	2684.3	2385.6	2716.3	1337	1968	1.19	1.07
18.08.2009	7.54	7.53	2199.5	2833.6	2213.7	2858.8	1536	2058	0.95	1.22
20.10.2009	7.29	7.54	2465.7	3576.4	2581.7	3623.9	3074	2433	0.53	1.38
07.12.2009	7.84	7.61	2174.0	2694.9	2126.6	2709.8	700	1512	1.51	1.15
15.02.2010										
19.04.2010	7.86	7.54	2353.5	2610.3	2322.2	2668.7	739	1746	1.41	0.77
FF4										
02.06.2009	7.52	7.36	2367.3	2726.6	2350.3	2806.8	1267	2965	1.34	0.80
18.08.2009	7.43	7.44	2236.1	2995.1	2283.7	3063.5	1982	2699	0.72	0.98
20.10.2009	7.21	7.69	2360.4	3062.2	2491.4	3050.2	3429	1709	0.45	1.76
07.12.2009	7.85	7.55	2187.8	2577.7	2131.2	2604.3	673	1631	1.60	0.99
15.02.2010	7.81	7.56	1816.8	2067.4	1823.3		634	1292	0.70	0.46
19.04.2010	7.88	7.43	2234.5	2861.0	2201.5	2972.4	655	2494	1.35	0.64
FF5										
02.06.2009	7.83	7.69	2125.5	3281.1	2082.8	3274.1	727	1573	1.45	1.69
18.08.2009	7.47	7.60	2239.1	2496.7	2270.8	2494.8	1861	1545	0.85	1.29
20.10.2009	7.29	7.54	2465.7	3576.4	2573.0	3613.7	3083	2437	0.57	1.49
07.12.2009	7.81	7.70	2174.0	2740.2	2138.9	2731.1	769	1244	1.36	1.39
15.02.2010	7.94	7.61	1804.6	2494.0	1784.3		465	1593	0.98	0.63
19.04.2010	7.94	7.42	2374.9	3273.5	2321.6	3421.6	604	3324	1.70	0.78

BGD
9, 7783–7830, 2012

Table 5. List of living foraminiferal assemblages collected at the studied stations (FF1, FF4 and FF5) of Flensburg Fjord during June 2009 and April 2010, size fraction 63–2000 µm.

	Living foraminiferal species 0–1 cm > 63 µm	June 02.06.2009	%	August 18.08.2009	%	October 20.10.2009	%	December 07.12.2009	%	February 15.02.2010	%	April 19.04.2010	%
Station FF1	Species												
	Ammonia aomoriensis	25	25.3	37	16.7	132	48.7	23	43.4			69	61.1
	Elphidium albiumbilicatum	1	1.0	2	0.9	42	15.5	2	3.8			1	0.9
	Elphidium excavatum clavatum	5	5.1	28	12.7	53	19.6	4	7.5			7	6.2
	Elphidium excavatum excavatum	16	16.2	33	14.9	24	8.9	16	30.2			18	15.9
	Elphidium gerthi	1	1.0	16	7.2								
	Elphidium incertum	51	51.5	105	47.5	12	4.4	8	15.1			16	14.2
	Total number of calcareous individuals	99		221		263		53				111	
	Ammotium cassis											1	0.9
	Reophax dentaliniformis					8	3.0					1	0.9
	Total number of agglutinated individuals	0		0		8		0				2	
	Total number of living specimens	99		221		271		53				113	
	Species number	6		6		6		5				7	
	Sample volume (cm^3)	47		76		56		60				94	
	Split (n)	0.5252		0.4585		0.4802		0.4791				0.5210	
	Population density (ind. 10 cm^{-3})	40.1		63.4		100.8		18.4				23.1	
	Shannon-Wiener-Index	1.23		1.43		1.42		1.33				1.17	
	Fisher's alpha	1.41		1.14		1.09		1.35				1.65	
Station FF4	Species												
	Ammonia aomoriensis	3	8.3	9	9.3	2	2.6	4	4.5	2	1.1		
	Elphidium albiumbilicatum			4	4.1								
	Elphidium excavatum clavatum			11	11.3	1	1.3						
	Elphidium excavatum excavatum			19	19.6	1	1.3						
	Elphidium gerthi												
	Elphidium incertum	28	77.8	51	52.6	57	74.0	52	59.1	160	92.0	77	93.9
	Total number of calcareous individuals	31		94		61		56		162		77	
	Ammotium cassis	2	5.6	1	1.0	15	19.5	32	36.4	12	6.9	5	6.1
	Reophax dentaliniformis	3	8.3	2	2.1	1	1.3						
	Total number of agglutinated individuals	5		3		16		32		12		5	
	Total number of living specimens	36		97		77		88	100	174		82	
	Species number	4		7		6		3		3		2	
	Sample volume (cm^3)	59		95		100		93		73		59	
	Split (n)	0.0663		0.2351		0.5080		0.4769		0.4913		0.0623	
	Population density (ind. 10 cm^{-3})	92.0		43.4		15.2		19.8		48.5		223.0	
	Shannon-Wiener-Index	0.77		1.38		0.81		0.82		0.31		0.23	
	Fisher's alpha	1.15		1.73		1.52		0.60		0.52		0.37	
Station FF5	Species												
	Ammonia aomoriensis	13	14.9	12	7.0	63	72.4	64	28.6	6	6.6	5	5.7
	Elphidium albiumbilicatum	8	9.2	2	1.2	2	2.3	19	8.5	1	1.1		
	Elphidium excavatum clavatum	12	13.8			3	3.4	24	10.7			1	1.1
	Elphidium excavatum excavatum	29	33.3	4	2.3	12	13.8	63	28.1	2	2.2	1	1.1
	Elphidium gerthi	1	1.1			3	3.4	1	0.4				
	Elphidium incertum	18	20.7	44	25.7	4	4.6	50	22.3	47	51.6	69	79.3
	Total number of calcareous individuals	81		62		87		221		56		76	
	Ammotium cassis	1	1.1	108	63.2			1	0.4	34	37.4	11	12.6
	Reophax dentaliniformis	5	5.7	1	0.6			2	0.9	1	1.1		
	Total number of agglutinated individuals	6		109		0		3		35		11	
	Total number of living specimens	87		171		87		224	100	91		87	
	Species number	8		6		6		8		6		5	
	Sample volume (cm^3)	47		67		51		64		76		48	
	Split (n)	0.1239		0.5340		0.1324		0.5071		0.5456		0.2996	
	Population density (ind. 10 cm^{-3})	149.3		47.8		128.9		69.0		21.9		60.5	
	Shannon-Wiener-Index	1.74		1.00		0.97		1.59		1.07		0.71	
	Fisher's alpha	2.15		1.21		1.46		1.62		1.44		1.15	

BGD
9, 7783–7830, 2012

Table 6. Foraminiferal census data of dead species collected at the studied stations (FF1, FF4 and FF5) of Flensburg Fjord during June 2009 and April 2010, size fraction 63–2000 µm.

	Dead foraminiferal species 0–1 cm > 63µm	June 02.06.2009	%	August 18.08.2009	%	October 20.10.2009	%	December 07.12.2009	%	February 15.02.2010	%	April 19.04.2010	%
Station FF1	Species												
	Ammonia aomoriensis	343	72.2	941	59.5	213	54.9	377	59.1			369	64.1
	Elphidium albiumbilicatum	1	0.2	3	0.2			2	0.3			2	0.3
	Elphidium excavatum clavatum	29	6.1	115	7.3	61	15.7	56	8.8			42	7.3
	Elphidium excavatum excavatum	8	1.7	183	11.6	68	17.5	114	17.9			92	16.0
	Elphidium gerthi	2	0.4			1	0.3	2	0.3				
	Elphidium incertum	87	18.3	296	18.7	38	9.8	63	9.9			64	11.1
	Total number of calcareous individuals	470		1538		381		614				569	
	Ammotium cassis	4	0.8	10	0.6			3	0.5			1	0.2
	Reophax dentaliniformis	1	0.2	33	2.1	7	1.8	21	3.3			6	1.0
	Total number of agglutinated individuals	5		43		7		24				7	
	Total number of specimens	475		1581		388		638				576	
	Species number	8		7		6		8				7	
	Sample volume (cm^3)	47		76		56		60				94	
	Split (n)	0.5252		0.4585		0.4802		0.4791				0.5210	
	Abundance (tests $10cm^{-3}$)	192.4		453.7		144.3		221.9				117.6	
	Shannon-Wiener-Index	0.87		1.19		1.24		1.23				1.09	
	Fisher's alpha	1.37		0.94		1.01		1.29				1.12	
Station FF4	Species												
	Ammonia aomoriensis	1	8.3	19	52.8	142	49.1	353	85.9	38	40.4	7	38.9
	Elphidium albiumbilicatum												
	Elphidium excavatum clavatum			3	8.3	8	2.8			2	2.1		
	Elphidium excavatum excavatum	3	25.0	4	11.1	1	0.3						
	Elphidium gerthi			1	2.8								
	Elphidium incertum	1	8.3	1	2.8	55	19.0	26	6.3	38	40.4	8	44.4
	Total number of calcareous individuals	5		28		206		379		78		15	
	Ammotium cassis	6	50.0	6	16.7	63	21.8	11	2.7	9	9.6	2	11.1
	Reophax dentaliniformis	1	8.3	2	5.6	20	6.9	21	5.1	7	7.4	1	5.6
	Total number of agglutinated individuals	7		8		83		32		16		3	
	Total number of specimens	12		36		289		411		94	100	18	
	Species number	5		7		6		4		5		4	
	Sample volume (cm^3)	59		95		100		93		73		59	
	Split (n)	0.0663		0.2351		0.5080		0.4769		0.4913		0.0623	
	Abundance (tests $10\,cm^{-3}$)	30.7		16.1		56.9		92.7		26.2		49	
	Shannon-Wiener-Index	1.31		1.45		1.30		0.55		1.23		1.13	
	Fisher's alpha	3.22		2.59		1.07		0.62		1.13		1.59	
Station FF5	Species												
	Ammonia aomoriensis	3	12.5	279	43.5	23	62.2	94	39.8	225	31.4	93	45.8
	Elphidium albiumbilicatum	1	4.2	11	1.7			2	0.8	2	0.3	1	0.5
	Elphidium excavatum clavatum	2	8.3	196	30.6	8	21.6	100	42.4	292	40.8	49	24.1
	Elphidium excavatum excavatum	10	41.7	4	0.6	2	5.4	1	0.4			3	1.5
	Elphidium gerthi		0.0					1	0.4				
	Elphidium incertum	7	29.2	137	21.4	3	8.1	33	14.0	165	23.0	53	26.1
	Total number of calcareous individuals	23		627		36		231		684		199	
	Ammotium cassis	1	4.2	6	0.9			2	0.8	22	3.1	3	1.5
	Reophax dentaliniformis			8	1.2	1	2.7	3	1.3	10	1.4	1	0.5
	Total number of agglutinated individuals	1		14		1		5		32		4	
	Total number of specimens	24		641		37		236		716		203	
	Species number	6		7		5		8		6		7	
	Sample volume (cm^3)	47		67		51		64		76		48	
	Split (n)	0.1239		0.5340		0.1324		0.5071		0.5456		0.2996	
	Abundance (tests $10cm^{-3}$)	41.2		179.2		54.8		72.7		172.7		141.2	
	Shannon-Wiener-Index	1.46		1.25		1.09		1.19		1.25		1.23	
	Fisher's alpha	2.57		1.10		1.56		1.60		0.898		1.406	

BGD
9, 7783–7830, 2012

K. Haynert et al.

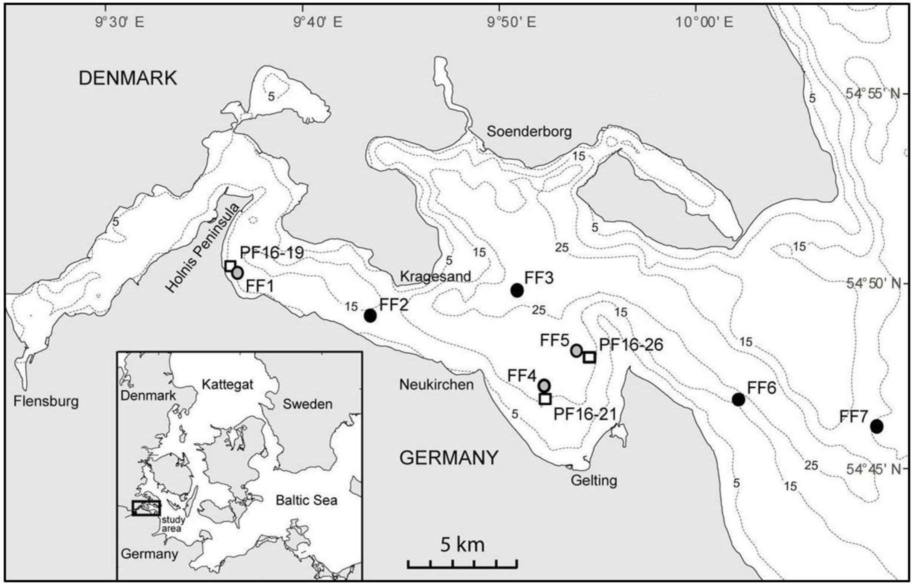

Fig. 1. Map of study area of Flensburg Fjord (design by courtesy of Anna Nikulina, GEOMAR). Insert indicates the location of study area within the SW Baltic Sea. Circles display sediment corer (FF1, FF4 and FF5) and water chemistry stations (FF1-FF7). White squares indicate sampling stations PF16-19, PF16-21 and PF16-26 of Polovodova (2008) in June 2006.

BGD
9, 7783–7830, 2012

BGD

9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

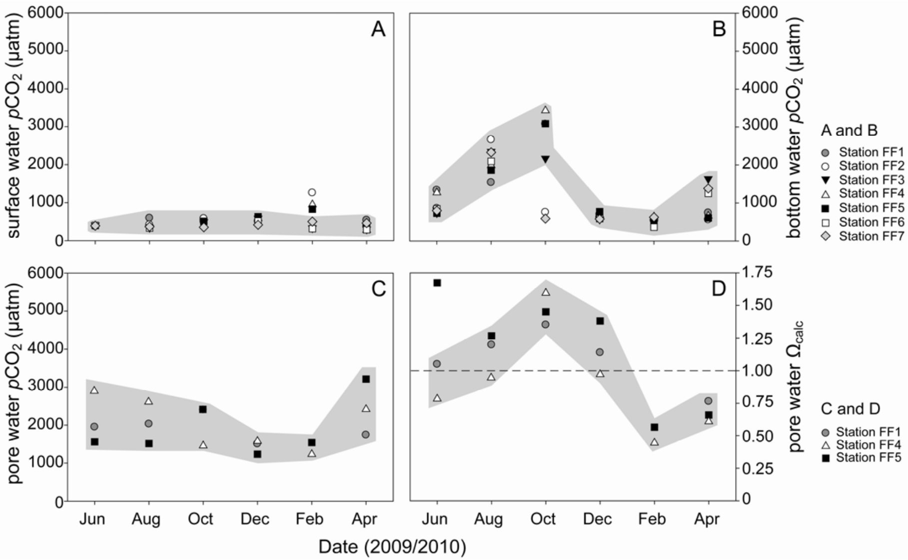

Fig. 2. (**A** and **B**) Surface water, near-bottom water, and bottom water pCO_2 at sampling stations from FF1 to FF7; (**C** and **D**) sediment pore water pCO_2 and Ω_{calc} at stations FF1, FF4 and FF5 from June 2009 to April 2010.

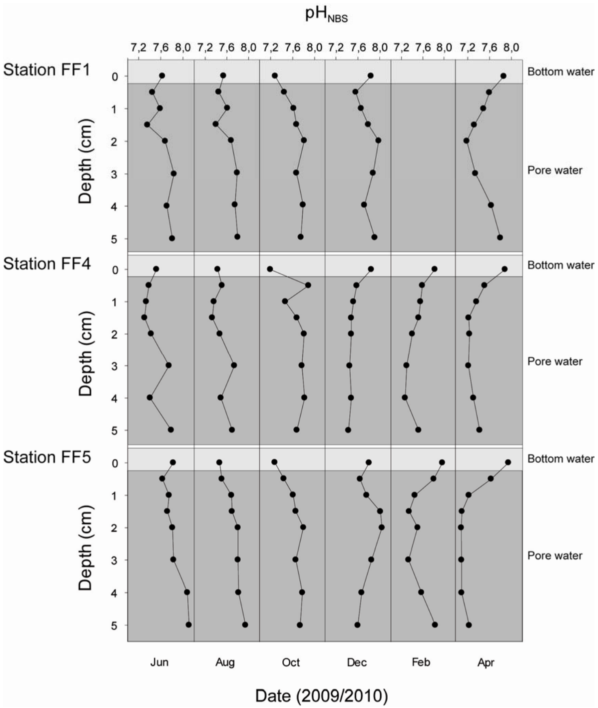

Fig. 3. Bottom and sediment pore water profiles of pH_{NBS} plotted vs. sediment depth (cm) at stations FF1, FF4 and FF5 during the seasonal cycle (2009/2010).

BGD
9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

BGD
9, 7783–7830, 2012

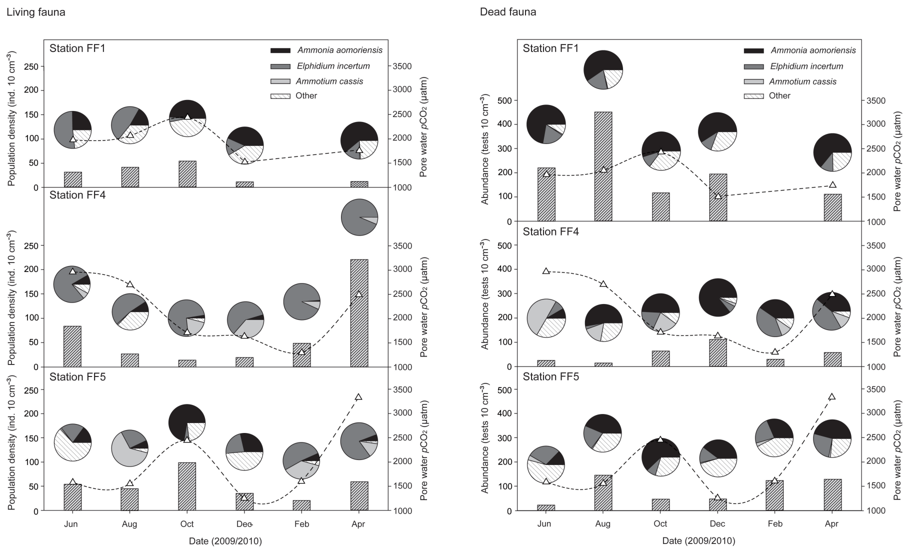

Fig. 4. Proportions and abundance of living and dead benthic foraminiferal species at stations FF1, FF4 and FF5 from June 2009 to April 2010. The bars present the population density and abundance of the living and dead fauna. Pie charts indicate the percentages of dominant species (Tables 5 and 6). Sediment pore water pCO_2 in Flensburg Fjord is displayed by white triangles.

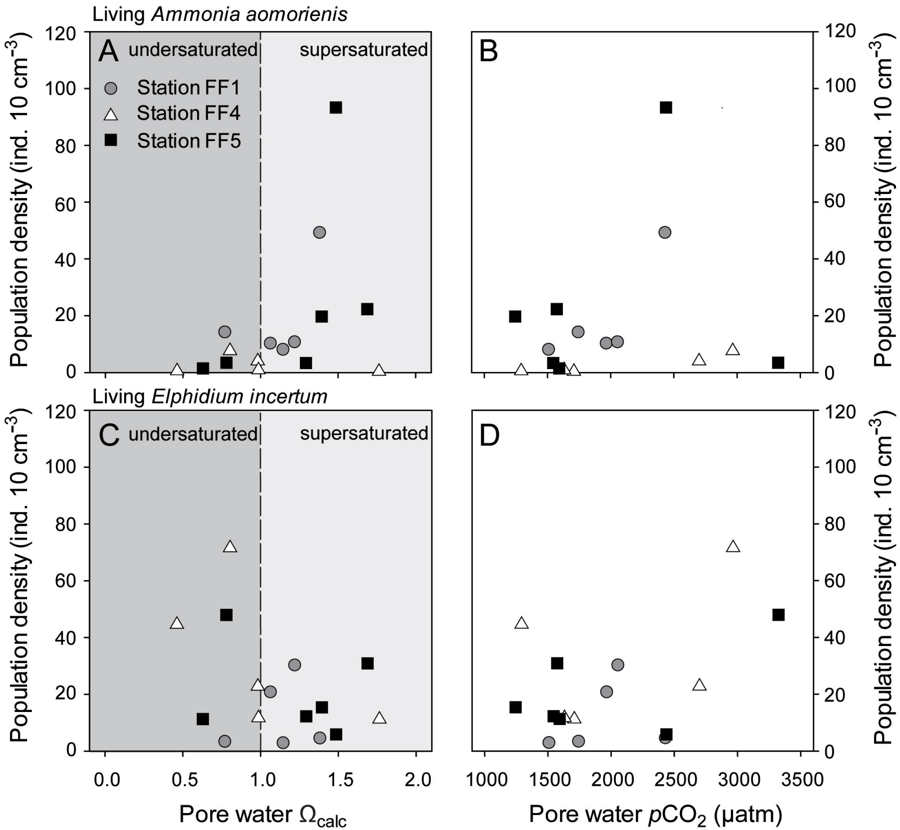

Fig. 5. Population density of living *A. aomoriensis* (**A** and **B**) and *E. incertum* (**C** and **D**) vs. sediment pore water Ω_{calc} (**A** and **C**) and pCO_2 (**B** and **D**). The different symbols present stations FF1, FF4 and FF5 during the one year cycle.

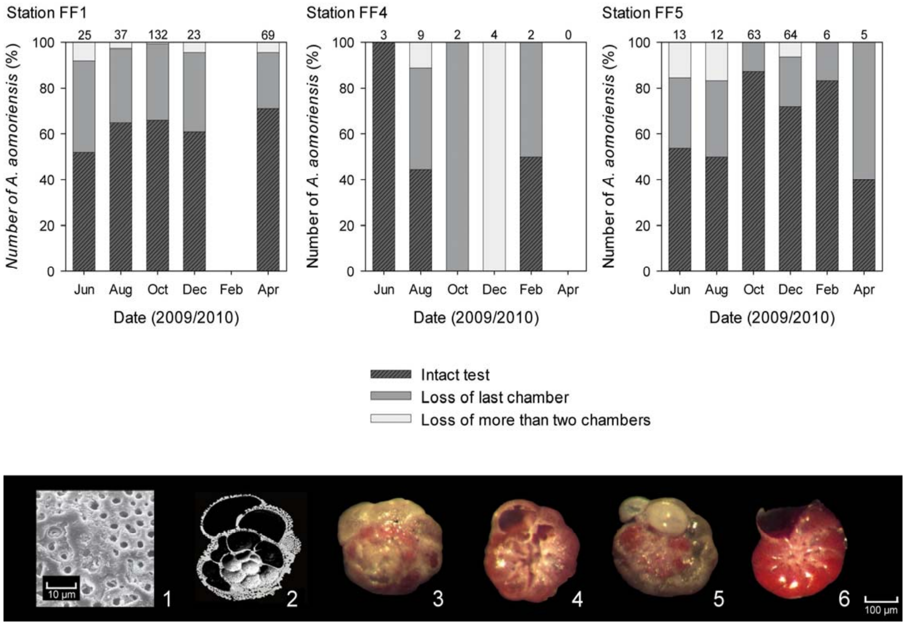

Fig. 6. Three stages of preservation of living *A. aomoriensis*: (1) intact tests, (2) loss of the last chamber and (3) loss of more than two chambers. Bars indicate the percentage of total species number of *A. aomoriensis* (Table 5) from June 2009 to April 2010. The number of counted *A. aomoriensis* specimens is present above each bar. Subjacent SEM (1), EPMA (2) and light micrographs (3–6) of *A. aomoriensis* and *E. incertum* tests from Flensburg Fjord from Station FF5 in June 2009. 1–5 *A. aomoriensis:* detailed view of recalcifying test (1), spiral (2, 3 and 5) and umbilical (4) views of recalcifying (2 and 3) and dissolved tests (4 and 5). 6: spiral view of *E. incertum* with intact test, last chamber was broken.

BGD
9, 7783–7830, 2012

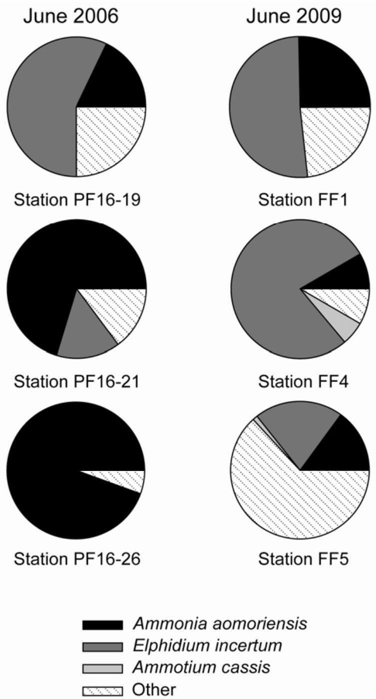

Fig. 7. Comparison of living benthic assemblages between the years 2006 and 2009.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

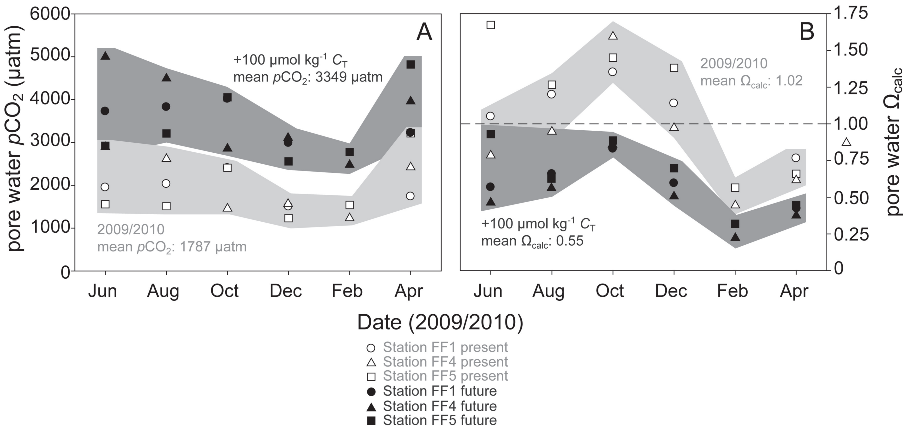

Fig. 8. Present **(A)** and future **(B)** sediment pore water pCO_2 and Ω_{calc} at stations FF1, FF4, and FF5. Future sediment pore water pCO_2 and Ω_{calc} were replotted from Table 4 and calculated after addition of 100 µmol kg^{-1} of C_T to C_T from Table 4.

BGD

9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

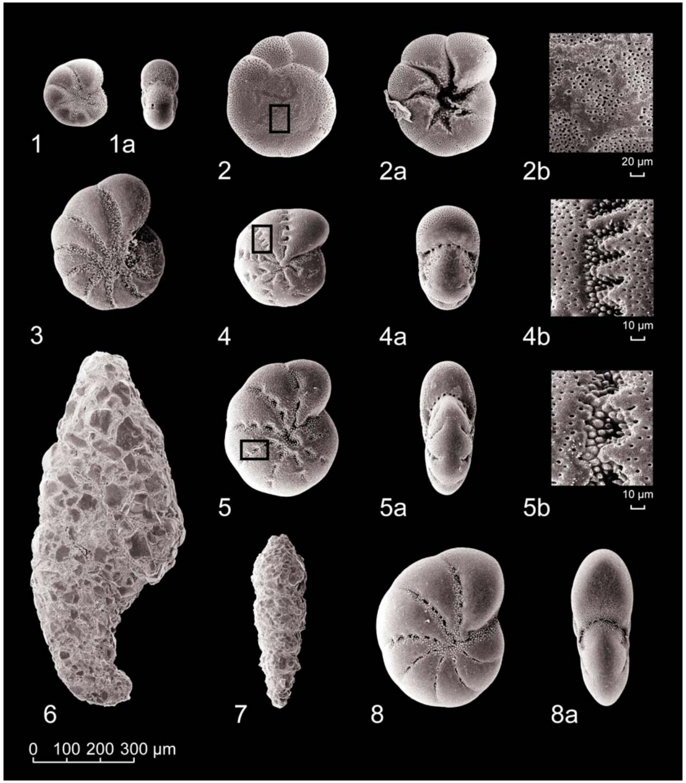

Fig. 9. Benthic foraminifera from Flensburg Fjord. 1 *Elphidium albiumbilicatum*: spiral (1) and apertural (1a) views; 2 *Ammonia beccarii*: spiral (2), umbilical (2a) and detailed view of the test wall (2b); 3 *Elphidium gerthi*: spiral view; 4 *Elphidium excavatum clavatum*: spiral (4), apertural (4a) and detailed view of the suture of two chambers (4b); 5 *Elphidium excavatum excavatum*: spiral (5), apertural (5a) and detailed view of the suture of two chambers (5b); 6 *Ammotium cassis*: top view; 7 *Reophax dentaliniformis*: top view; 8 *Elphidium incertum*: spiral (8) and apertural (8a) views.

BGD
9, 7783–7830, 2012

The benthic foraminiferal community

K. Haynert et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀I
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion