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Benthic foraminifera distribution in the modern sediments of the South-eastern Baltic Sea with respect to North Sea water inflows

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Abstract. The hydrological regime of Baltic Sea bottom water is strongly influenced by irregular inflows of high-saline, oxygen-rich North Sea water through the narrow Danish Straits. The aim of this work was to study the interrelation between the distribution of benthic foraminifera in the South-Eastern Baltic Sea and hydrology of the bottom water. Benthic foraminiferal distribution was analyzed in the 26 surface sediment samples, collected in the Baltic Sea during spring and winter 2016. Micropaleontological data were compared to the changes in dissolved oxygen content and the salinity of the bottom water. The species diversity of the benthic foraminifera in the studied region was very low. Agglutinated species, mostly single-chambered, were the most abundant in the assemblages. The distribution of the foraminiferal concentrations in the sediments had similar spatial patterns in both

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seasons. High shell concentrations as well as increase in faunal diversity were identified at the deeper parts of the study region where saline oxygen-enriched North Sea water is accumulated. Maximum foraminiferal concentration was found in the sediments of the Gdansk-Gotland Sill where halocline reaches the bottom which favors nutrient accumulation. However, the sharp dominance of very small individuals of Pseudothurammina shows that only some species can survive in the variable conditions associated with the halocline.

1 Introduction

The Baltic Sea is a brackish, semi-enclosed water body, with a stratified water column and restricted exchange of deep waters. The hydrological and hydrochemical regime of isolated bottom water is strongly influenced by irregular inflows of high-saline oxygen-rich North Sea water through the narrow Danish Straits [*Hausler,* 2017; *Hermelin,* 1987; *Mohrholz et al.,* 2015]. As a result of mixing, the salinity decreases in northeastern direction, affecting both the reduction in diversity and density of populations, as well as in the average size of individuals [*Hermelin,* 1987].

Over the past twenty years the decrease in frequency of the major Baltic inflows (MBI), amplified by anthropogenic eutrophication and climate change, caused the expansion of oxygen deficiency zones in the bottom water layer [*Carstensen et al.,* 2014].

Information on the regional hydrology in the past is necessary to improve our understanding of the environmental and climate evolution in the Baltic Sea, to assess the natural component of these changes, and to develop reliable forecasts. Data on the benthic foraminifera distribution in the sediment cores can be used in paleoceanological reconstruction; however, a reliable paleoecological interpretation requires information about current species ecology, in particular, the data on the quantitative and qualitative distribution of benthic foraminifera in relation to the bottom salinity [*Murray and Alve,* 2011].

Studies of the distribution of benthic foraminifera in the surface sediments of the exclusive economic zone of Russia in the Baltic Sea are represented by a few works, for example [*Lukashina,* 1995; *Saidova,* 1981]. Such a small number of studies can be explained by low abundance of foraminifera and poor shells preservation, which significantly complicates micropaleontological analysis [*Frenzel et al.,* 2005].

The aim of this study is to describe the distribution of recent benthic foraminifera in relation to hydrology and hydrochemistry of the bottom waters.

2 Materials and Methods

2.1 Study Region

The morphology of the Baltic Sea includes several subbasins, connected by channels. Dense and salty North Sea water flows from the Arcona Basin to the Bornholm Basin through the Hamrarne Strait (Bornholmsgat) below the pycnocline [*Kabel et al.,* 2012]. Then inflow water spreads further via the Stolpe Furrow to the Gotland and Gdansk basins, located in the southeastern part of the Baltic Sea and separated from the Gotland Basin by the Gdansk-Gotland Sill [*Binczewska et al.,* 2017; *Hausler,* 2017; *Mohrholz et al.,* 2015].

The data for this study were collected in the 131st cruise of the R/V *Professor Shtokman* (March–April 2016, PSh131) and the 33rd cruise of the R/V *Akademik Nikolai Strakhov* (October–December 2016, ANS33). In the spring of 2016, sediment samples were taken with the OCEAN-50 sediment grab at 19 stations in the Russian sector of the Southeastern Baltic

Sea (Gdansk Basin and slope of the Gotland Basin). In winter, sampling stations were located along the western border of the Russian sector of the sea (5 stations) and also in the Bornholm Basin (2 stations) (Figure 1). The average depth of the sea in the study region located in the Bornholm Basin is 89 m. In the Gdansk Basin, the sediments were collected at the water depths from 25 to 106 m. The depth of the sea at the stations performed on the slope of the Gotland Basin reached 85–109 m.

2.2 Hydrology and Hydrochemistry

Together with the sediments sampling, the salinity and temperature of the water column were measured by the Sea&Sun CTD90M profiler. The water from the bottom layer was sampled with the HYDRO-BIOS Multi Water Sampler MWS 12 Slimline, the dissolved oxygen content was determined by the Winkler method. In addition, we used the hydrological data collected in the 134th cruise of the R/V *Professor Shtokman* (31 October 2016) in the Russian sector of the South-Eastern Baltic Sea.

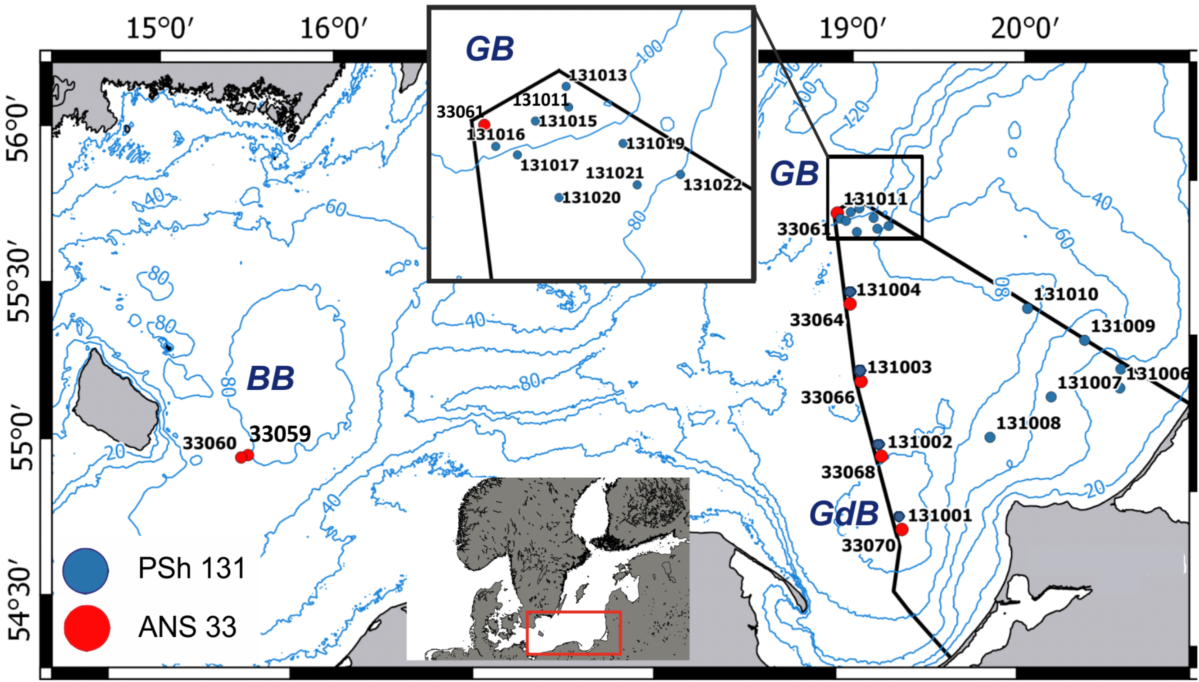

Figure 1. Map of the study site. Dots indicate the sampling stations during the 131st cruise of the R/V *Professor Shtokman* (March–April 2016, PSh131) and the 33rd cruise of the R/V *Akademik Nikolai Strakhov* (October–December 2016, ANS33). (BB is the Bornholm Basin, GB is the Gotland Basin, GdB is the Gdansk Basin).

2.3 Micropaleontology

The top undisturbed sediment layer one centimeter thick was used as the material for the micropaleontological analysis. The bottom sediments (26 samples) were weighed in wet condition, washed over 63 μm sieve and dried. The given size of a sieve mesh allows us to take into account small shells of foraminifera, which are characteristic for the brackish water environment. The concentration of benthic foraminifera and the species composition of the fauna were determined in a dry sand fraction and were counted per gram of total dry sediment. In micropalaeontological analysis, both living and dead foraminiferal communities were used. This approach allows us to study the general regularities of foraminiferal distribution, which was the task of the current study. Living fauna is sensitive to the heterogeneities of environment and seasonality, while the data on combine living plus dead fauna and tanatocenosis reflect the averaged long-term conditions and can serve as an analogue of fossil assemblages in the study area [*Murray and Alve,* 2011]. Wet counting was additionally applied to the samples taken in the 33rd cruise of the R/V *Akademik Nikolai Strakhov*. As described in [*Binczewska et al.,* 2017; *Brodniewicz,* 1965], this method of sample preparation is used to avoid agglutinated tests breakage, which represent the majority of the population in the Baltic Sea.

2.4 Data Processing

Statistical analysis of the study results was applied to reveal the interrelationships between the distribution of the hydrological and hydrochemical parameters and the micropaleontological data. Correlation matrices, including the significance of correlation (t-test), were calculated using the STATISTICA 10 software.

3 Results and Discussion

3.1 Hydrology and Hydrochemistry

According to the distribution of hydrological and hydrochemical parameters in spring and winter of 2016 in the southeastern part of the Baltic Sea, the water column had two-layer vertical structure, the halocline was located at a depth of 60–90 (in spring) and 70–76 m (in winter). During both cruises, the salinity and temperature of the bottom water were greater than the mean values above the Gdansk-Gotland Sill at the time of the bottom sediments sampling: > 12 PSU; $> 6.5^\circ$C (spring) and $> 8^\circ$C (winter). These parameters reached anomalously high values in the center of the Gdansk Basin during the spring and winter cruises (13–14.5 PSU and 7.5–8.5°C), indicating the advection of water from the western regions of the Baltic Sea. However, the concentrations of dissolved oxygen in the near-bottom water layer in the Gdansk Basin were significantly higher in spring (3.5–4.5 ml/l) compared to the winter values (0–1.5 ml/l), which is an evidence of the relatively "old" water, that was transported from the Stolpe Furrow in autumn. This conclusion is supported by the results of hydrological study in the 134th cruise of the R/V *Professor Shtokman* on 31 October 2016. During the cruise the increased concentrations of dissolved oxygen (4.7 ml/l) were measured in the same area. The salinity and temperature of the bottom water were relatively high (> 18 PSU and 10.3–7.5°C) in the Bornholm Basin in December 2016. The content of dissolved oxygen in the bottom water was 3.1 ml/l.

Thus, the distribution of temperature and salinity in the bottom water layer allows us to conclude that in the spring and winter of 2016 advection of the significant volume of North Sea water preceded both cruises.

3.2 Micropaleontology

The distribution of the benthic foraminiferal concentrations in the sediments has similar spatial pattern in both seasons. However, the values, measured in December, were one order of magnitude higher than in March and April (Figure 2). On the slope of the Gdansk Basin, the concentration of foraminifera was 0.3 shells/g (spring) and 2.5 shells/g (winter), while in the basin, the increased values (1.9 and 17.6 shells/g, respectively) were recorded. Maximum concentrations of foraminifera were found in the sediments of the Gdansk-Gotland Sill: 4.7 shell/g (spring) and 85.9 shells/g (winter). On the slope of the Gotland Basin, the concentration of foraminifera increased with depth, reaching 0.6 and 28.1 shell/g in spring and winter, respectively. In the sediments of the Bornholm Basin, the average amount of shells per gram of dry sediment was higher than in the Gdansk Basin in both seasons and reached 36 shell/g.

The species diversity of the benthic foraminifera in the study region was very low, which is also noted in the works, describing the western regions of the sea [*Brodniewicz,* 1965; *Binczewska et al.,* 2017; *Hermelin,* 1987; *Murray and Alve,* 2011; *Polovodova et al.,* 2009]

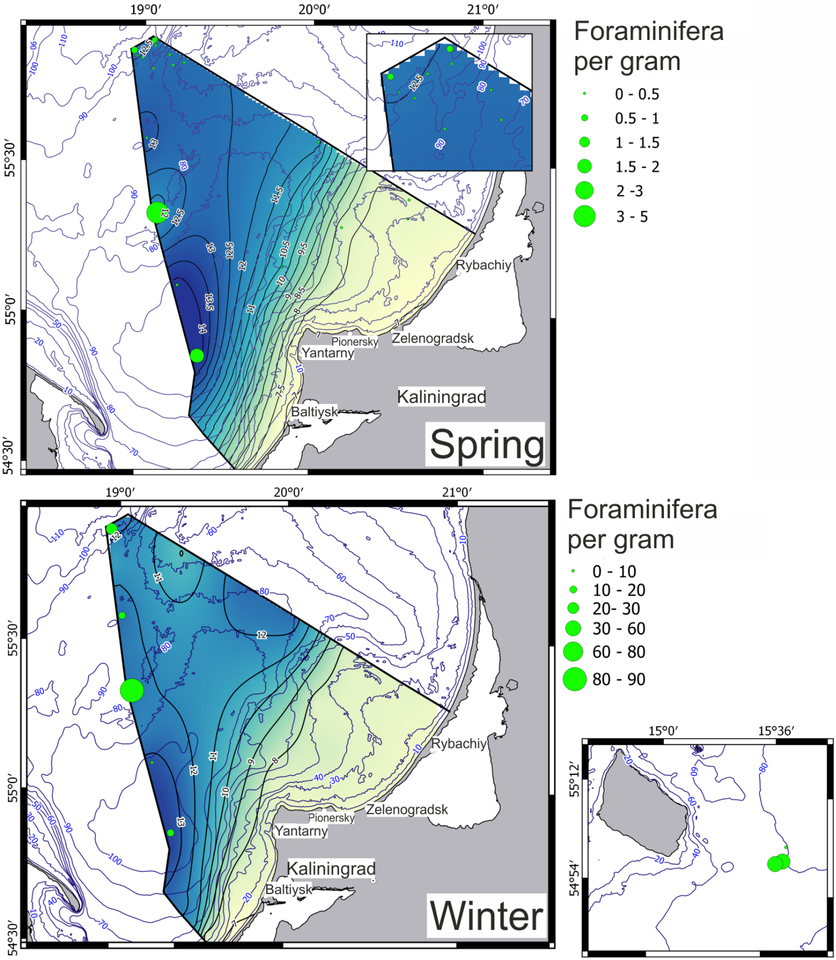

Figure 2. Distribution of salinity (isohalines) and benthic foraminifera concentrations in spring (PSh131) and winter (ANS33) of 2016 in the Southeastern Baltic Sea. The stations located in the Bornholm Basin are shown on the additional map.

(Figure 3). As was also observed in the studies of [*Alve and Murray,* 1999; *Brodniewicz,* 1965; *Hermelin,* 1987], agglutinated species are the most abundant in the assemblages. They were dominated by small sized individuals (less than 100 μm) of a simple single-chamber structure, which belong to Psammosphaera, Pseudothurammina and Saccammina genera, and also Reophax species. The decrease in the size of benthic foraminifera in the Baltic Sea was also mentioned in the other papers [*Brodniewicz,* 1965; *Binczewska et al.,* 2017; *Hermelin,* 1987], as the response of the organisms to reduced salinity.

In the Gdansk Basin, carbonate shells were found only at the stations, situated in the depressions and characterized by anomalously high salinity ($>$ 13 PSU), while in the Bornholm Basin they were found at all stations. As was already shown in [*Binczewska et al.,* 2017; *Brodniewicz,* 1965; *Hausler,* 2017] that calcareous species were dominated by Cribroelphidium (Elphidium) genus. Species of this genus are characterized as opportunistic and euryhaline occurring under the conditions of increased productivity and reduced oxygen and salinity (up to 11–12 PSU) [*Binczewska et al.,* 2017; *Brodniewicz,* 1965; *Hausler,* 2017; *Kaiho,* 1994; *Lutze,* 1965; *Murray,* 2006].

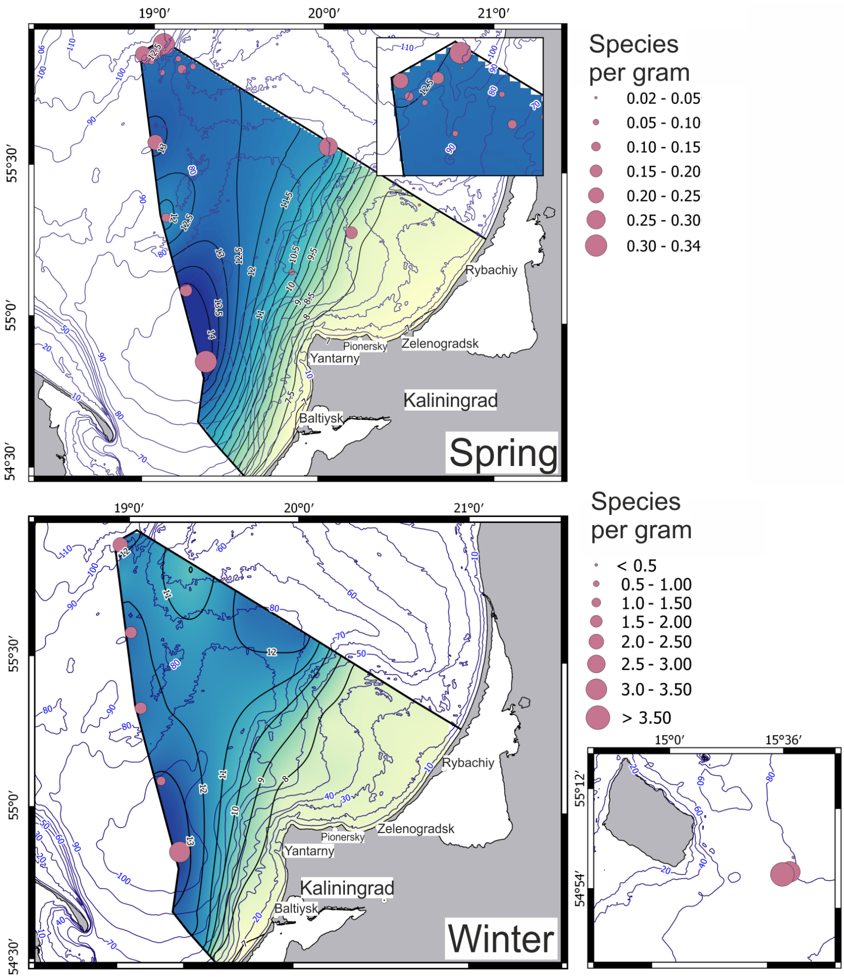

Figure 3. Distribution of salinity (isohalines) and benthic foraminifera species in the spring (PSh131) and winter (ANS33) periods of 2016 in the Southeastern Baltic Sea. The stations located in the Bornholm Basin are shown on the additional map.

3.3 Data Processing

The data analysis revealed that the distribution of benthic foraminifera in the surface sediments demonstrates a good correlation with the hydrological parameters. High foraminifera concentrations as well as an increase in faunal diversity corresponded to the deeper parts of the study region: the Bornholm and Gdansk basins and the slope of the Gotland Basin. Saline, oxygen-rich North Sea water is accumulated in these depressions creating favorable conditions for the life of foraminifera. Benthic foraminifera diversity demonstrated a significant correlation with the salinity of the bottom waters (correlation coefficients (R) $=$ 0.7). However, no high correlation was revealed between the distribution of foraminifera concentration in the sediments and salinity (R $=$ 0.4). The maximum concentration of foraminifera determined in the sediments of the Gdansk-Gotland Sill can be associated with the depth of halocline. However, the sharp dominance of very small (up to 100 microns) single-chamber Pseudothurammina individuals indicates that only some species can adapt to the variable environmental conditions associated with the halocline [*Conradsen,* 1993].

4 Conclusions

The diversity of the benthic foraminifera species in the Southeastern Baltic Sea was very low. Small size agglutinated individuals dominated in the foraminifera assemblages. Increase in foraminifera concentrations and in assemblages diversity were found in the deeper parts of the study region, where saline, oxygen-rich North Sea water is accumulated. The characteristics of bottom water salinity showed significant correlation with the species diversity rather than with the amount of shells in sediments. The revealed dependencies support the future application of benthic foraminiferal distribution in sediment cores for the reconstruction of saline water inflows into the Southeastern Baltic Sea. The long datasets on the environmental conditions in this area is necessary for model prediction of future changes in the Baltic Sea system.

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