Variability of hydrological and hydrochemical conditions of Gotland and Gdansk Basins' bottom waters (Baltic Sea) in 2015–2016

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The field data set obtained in 2015–2016 in the south-eastern part of the Baltic Sea within the exclusive economic zone (EEZ) of the Russian Federation revealed a rise in the values of the hydrological characteristics of the Gdansk and Gotland (southern slope) Basins bottom layer. It was caused by the increased frequency of the North Sea water intrusions and their advection into the bottom layer of basins. As a result of these intrusions the hydrochemical conditions of the near-bottom waters has changed. The highest values of the dissolved oxygen content coincided with the extremes of salinity and temperature. The content of phosphates and silica increased simultaneously with the decrease of concentration of dissolved oxygen. The variability of the parameters for two basins was different. An increase in the temperature and salinity values on the southern slope of the Gotland Basin was less obvious than that in the Gdansk Basin. The concentrations of dissolved oxygen within the Gotland Basin in the most cases (besides the spring 2016) exceeded the values in the Gdansk Basin by 0.3–1.0 ml/l. The oxidation of the bottom sediment upper layer was observed in the Gotland Basin's southern slope, while the Gdansk Deep sediments had distinct hydrogen sulfide smell. The benthic communities of the Gotland were represented not only by the species which are tolerant to low dissolved oxygen content, but also by the young *Macoma balthica*. Anaerobic periods led to the absence of benthic macro- and meiofauna in the deep areas of the Gdansk Basin. *KEYWORDS:* Baltic Sea; marine biology; oxidation/reduction reactions; Major Baltic Inflow; anoxic environments; benthic processes; benthos.

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Introduction

The hydrological structure of the Baltic Sea is characterized by the presence of a permanent halocline. The surface and near-bottom water layers do not mix with each other. That leads to stagnation of bottom waters and formation of anoxic zones. The intrusions of the North Sea waters into the Baltic Sea is one of the most important factors, which form its hydrological, chemical and biological structures. This process is one of the main for the Baltic in the salt balance composition, and also the main one in enriching its bottom layers with oxygen [*Terziev et al.*, 1992]. From the

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1980s till the end of 2014, there has been a decrease in the North Sea water intrusions frequency (Major Baltic Inflows, MBI) from 5–7 per decade to 1 [*Mohrholz et al.,* 2015]. In December 2014, researchers from the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) has recorded a Major Baltic Inflow, which brought 198 km^3 of North Sea water and 3.98 Gt of salt to the Baltic (Naumann M., Mohrholz V., Nausch G. Baltic inflow of December 2014, The Leibniz Institute for Baltic Sea Research. February 2015. Available at: http://www.io-warnemuende.de/baltic-inflow-of-december-2014.html, accessed 10.01.2016).

On 14–22 November 2015 another MBI occurred: the Baltic Sea received 76 km^3 of water with salinity levels of 17–22 PSU. This led to the increase in salinity in the Arkona Basin bottom layer. At Arkona Becken station (54°53'N, 13°52'E), during the period from November 2015 to January 2016 and from February to the end of March 2016 salinity changed from 14 to 23 PSU in the bottom layer (43 m) (Data of the automated measuring stations (MARNET), Arkona Sea, Leibniz Institute for Baltic Sea Research Warnemünde. Available at: https://www.io-warnemuende.de/marnet-arkona-sea.html, accessed 18.01.2019).

The increase in the MBI's frequency has affected the South-Eastern Baltic, namely the exclusive economic zone (EEZ) of the Russian Federation; water temperature and salinity of the Gdansk Basin bottom layer and southern slopes of the Gotland Basin have also changed [*Krechik et al.,* 2017]. The aim of this study is to describe the changes in sedimentation conditions and hydrobiological parameters as a result of hydro-hydrochemical conditions change due to the advection of the North Sea waters into the bottom layer of the deep-sea basins of the South-Eastern Baltic Sea and their subsequent assimilation.

Materials and Methods

In 2015–2016 four cruises were carried out by the P. P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (IO RAS) on research vessels *Professor Shtokman* (30 March–6 April 2016), *Akademik Mstislav Keldysh* (29–30 October 2015), and the motorboat "Nord-3" (24–26 April 2015, 6–8 August 2015). These studies helped to obtain 20 profiles of vertical distribution of temperature and salinity, which were measured at 5 stations located in the study area (Figure 1). The data were obtained using multiparameter probe Sea & Sun Tech CTD90M.

Water samples were taken from the near-bottom layer by the Niskin sampling bottle. Analysis of the dissolved oxygen content was carried out onboard by the classical iodometric Winkler titration. Water samples for mineral forms of silicon and phosphorus were frozen. The phosphate content was measured using Murphy and Riley method [*Murphy and Riley,* 1962]. The analysis of the silica content was carried out by the colorimetry of the blue silicon-molybdenum complex [*Koroleff,* 1976]. Measurements were made on a mechanical photocolorimeter KFK 2-UHL 4 at a wavelength of 750 and 810 nm respectively.

Bottom sediments for geochemical analysis were collected by the Niemiste corer; sampling was carried out at every 1 cm. The manganese (Mn) content in the bottom sediments was determined by the method of flame atomic absorption spectrometry. The type of sediment was determined visually and organoleptically. Samples of benthic organisms were obtained by the Ocean-50 bottom grab (capture area 0.25 m^2, two probes per station). From that part of each grab with untouched sediments, meiobenthos samples were taken with the tubular sampler 2.8 cm diameter. The rest of the grab sample was washed with seawater from a circulation pump on a 0.4 mm sieve. Large organisms were removed and fixed immediately after washing. Remained organisms were fixed with 4% formalin. The samples treatment and identification of organisms were carried out according to standard methods.

Results and Discussion

According to the measurements, managed in April 2015, water advection from the western Baltic coast was indicated both in the southern part of the Gotland Basin (st. 5, Figure 1) and in the Gdansk Basin (st. 1, Figure 1). Water salinity maximum on the slope of the Gotland Basin was 12.0 PSU, while on bottom of the Gdansk Basin it was 14.3 PSU, which is 2.8 PSU higher than the mean annual value [*Feistel,* 2008]. The depth of

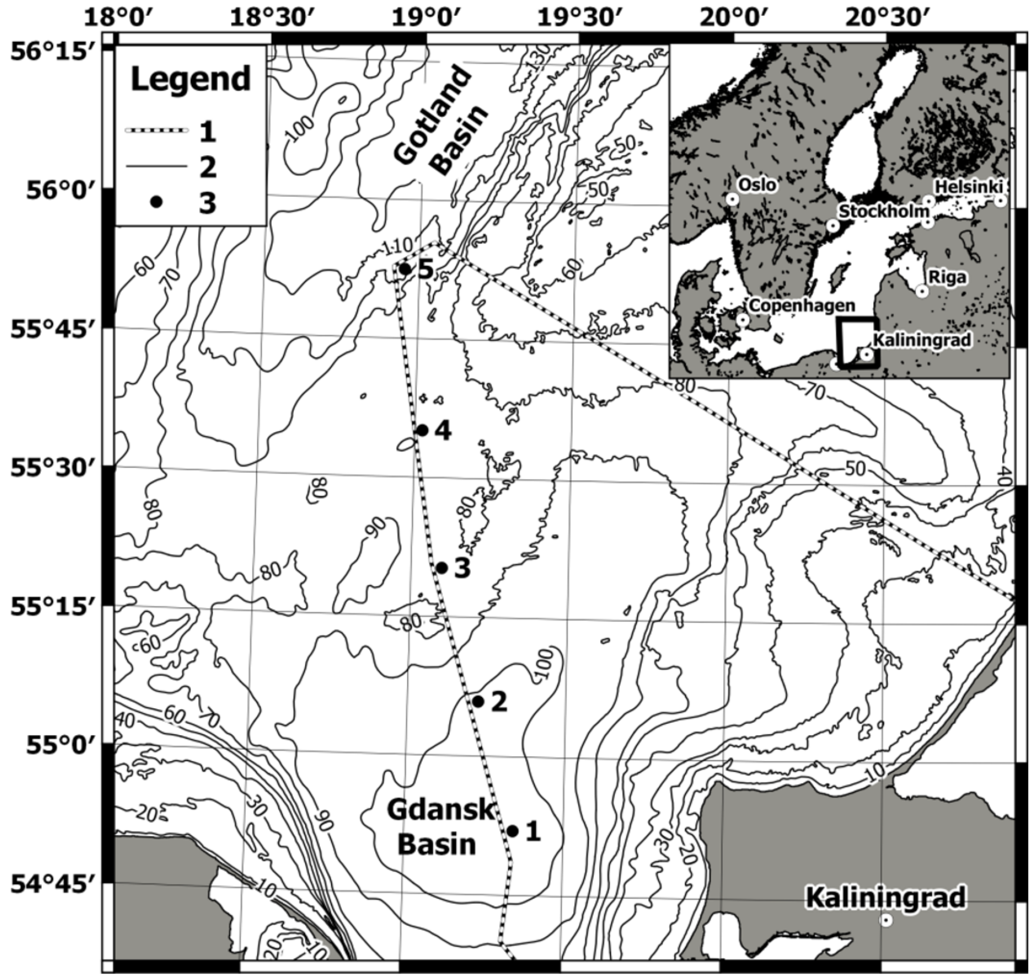

Figure 1. Study area. 1 – the border of the Russian Federation EEZ; 2 – isobaths, drawn every 10 m; 3 – the sampling stations.

halocline occurrence corresponded to the position of the main thermocline and varied from 65–70 to 80–100 m. The appearance of the inflow was also marked by high near bottom water temperature: namely > 6°C at station 5 and up to 7.6°C at station 1. At the same time, low dissolved oxygen content at the bottom did not allow us to define the water mass as the inflow water. Apparently, this water was the displaced volume from the Bornholm Basin. It should be noted that at station 5 the values of temperature, salinity and oxygen concentration at the bottom were lower than that at station 1.

In the summer and autumn of 2015, a steady decrease of bottom water salinity level in the Gdansk Basin was observed, precisely to 13.7–13.8 PSU in August and 13.5–13.6 PSU in November. In the southern part of the Gotland Basin, the bottom salinity rate was 11.45 PSU during this period. The temperature of the bottom layer in August was about 7.4°C, while in November it dropped to 7.2°C.

The oxygen concentration and salinity decrease in the bottom layer indicates a partial assimilation of the inflow waters in the research area during the spring. The temperature and salinity at the bottom from August to November remained almost stable, indicating the lack of water transport from other basins and the stabilization of the thermohaline structure under the pycnocline.

The new MBI occurred in the second half of November 2015 (Hentzsch B., Autumn gales again

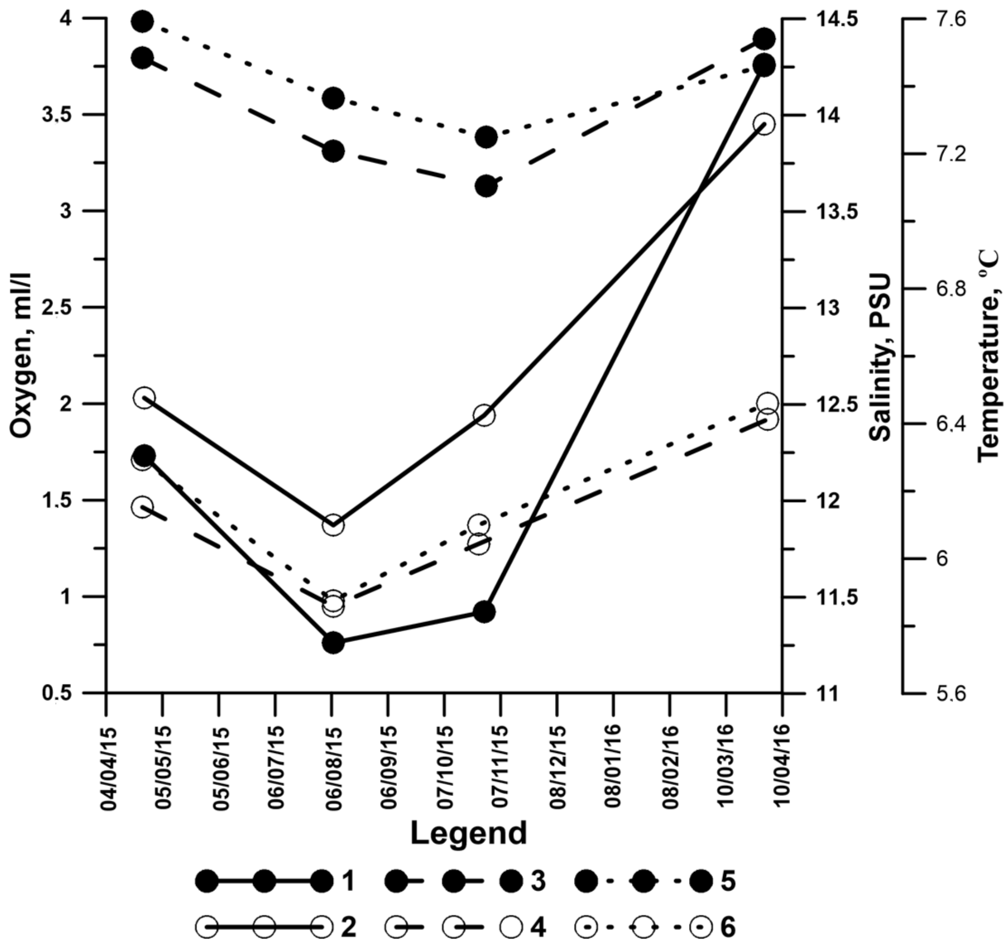

Figure 2. Changes in the concentration of dissolved oxygen, salinity and temperature in the bottom layer of the Gdansk and Gotland Basins from 24.04.2015 to 04.04.2016. 1 – concentration of oxygen at station 1; 2 – oxygen concentration at station 5; 3 – salinity at station 1; 4 – salinity at station 5; 5 – temperature at station 1; 6 – temperature at station 5.

drive salt into the Baltic: Third Major Baltic Inflow within 1.5 years. The Leibniz Institute for Baltic Sea Research. Available at: https://www.io-warnemuende.de/news-details/items/autumn-gales-again-drive-salt-into-the-baltic-third-major-baltic-inflow-within-15-years.html, accessed 28.01.2016), so sounding in the study area at the end of March 2016 revealed salinity and temperature rise up to 14.2 PSU and 7.4°C respectively near the Gdansk Deep bottom (100 m depth). The bottom salinity level at the area of Gotland-Gdansk Sill was 12.0–12.9 PSU, and at the southern slope of the Gotland Basin showed 12.4 PSU salinity rate.

Not only are hydrological conditions changing due to the arrival of North Sea waters in the Baltic Sea but hydrochemical and hydrobiological characteristics in the bottom layer [*Drozdov and Smirnov,* 2008] are also changing. It is known [*Cyberski,* 2011; *Terziev et al.*, 1994; *Soskin,* 1963] that the main marker of water transport from the Danish straits into the deep Baltic Sea layer, along with the increasing salinity, is an increase in the dissolved oxygen content. Figure 2 shows the oxygen content change along with the temperature and salinity levels in the near-bottom layer of the Gdansk Basin and on the slope of the Gotland Basin.

The highest dissolved oxygen concentrations were recorded in spring, coinciding with the peaks of salinity and temperature. Increased oxygen concentrations were observed in April 2015 (1.73 ml/l in Gdansk Basin and 2.03 ml/l on the slope of the Gotland Basin) with high values of T/S. The val-

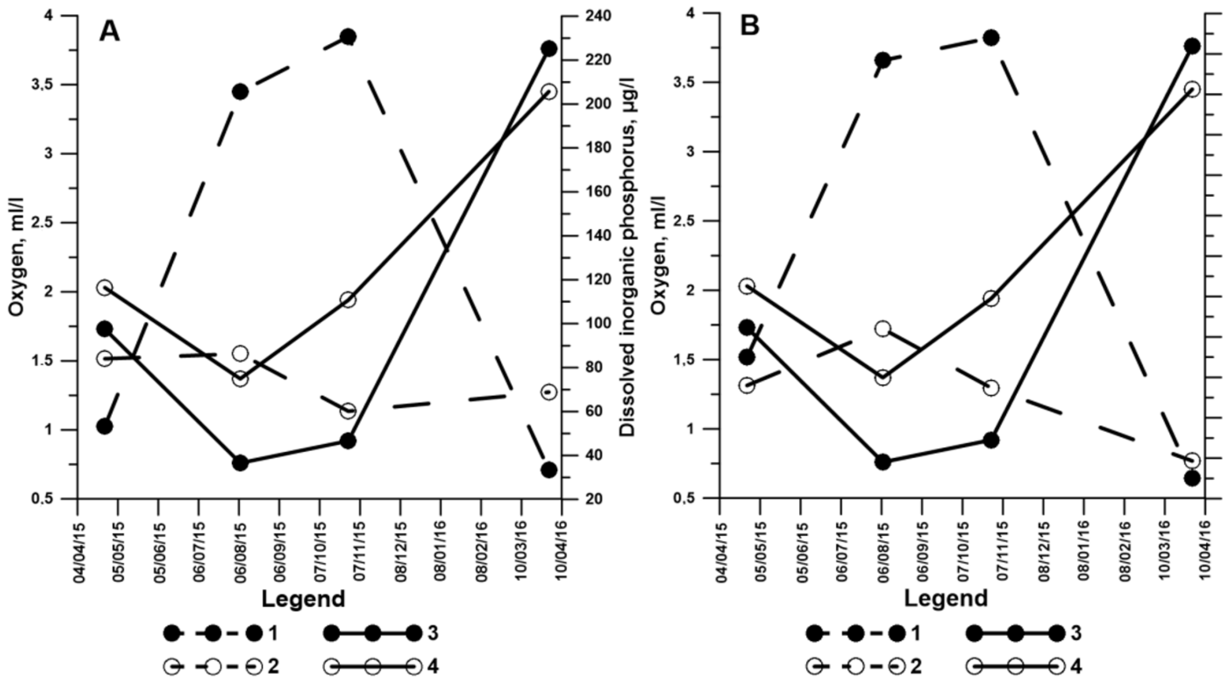

Figure 3. Variability of the concentration of inorganic phosphorus (a) and silica (b), along with the dissolved oxygen content in the bottom layer of the Gdansk and Gotland basins at the period from 24.04.2015 to 04.04.2016. 1 – concentration P for (A) and Si for (B) at station 1; 2 – concentration P for (A) and Si for (B) at station 5; 3, 4 – oxygen content at stations 1 and 5, accordingly.

ues reduced to 0.76 ml/l (station 1) and 0.92 ml/l (station 5) in the summer 2015 along with the decrease of the temperature and salinity values owing to the inflow waters assimilation. The slight rise in the dissolved oxygen content both at stations 1 and 5 was noted in the October 2015, while the temperature and salinity experienced increase only on the southern slope of the Gotland Basin. The surge in the oxygen and salinity level at both stations were recorded at the end of March 2016; the oxygen/salinity content in the Gdansk Basin was 3.76 ml/l and 14.39 PSU accordingly, while in the Gotland Basin the record showed 3.45 ml/l and 12.42 PSU. One of the observed features that should be noted is the fact that at lower temperatures and salinity the bottom layer at station 5 was better aerated over the entire research period.

The dissolved oxygen concentration in the bottom layer of the Baltic Sea significantly influences the content of phosphates and silicates [*Terziev et al.*, 1994]. So the concentration of phosphates sharply increases during the periods of anaerobic conditions in the deep-water areas of the Baltic Sea. The mechanism of their accumulation includes the formation of sparingly soluble phosphate compounds with ferric iron under oxidizing conditions, followed by sedimentation to the bottom [*Fonselius,* 1969]. Oxygen deficiency leads to the reduction of iron to divalent, forming highly soluble phosphate compounds. Then the reaction of iron with sulfate ions occurs, and phosphates are released into the water. The main process that determines the input of silicates into the deep layer of the Baltic Sea basins is the settling of siliceous remains and their subsequent dissolution. Transport processes mainly determine the change in the silica content in the bottom layer, but the occurrence of anaerobic conditions here is accompanied by a slight increase in silica content [*Terziev et al.*, 1994].

Changes in the concentration of inorganic phosphorus and silica during the study period had a similar course (Figure 3). At the same time, significant differences in the values of both elements were observed at stations 1 and 5.

The Gdansk Deep (station 1) shows that the minimum values of P and Si content appeared to be simultaneous with the maximum oxygen level and were caused by a change from reducing to oxidative conditions. At the time the concentration of dissolved oxygen decreased, the content of phosphates and silicates increased. The peak value of nutrients was recorded in October 2015 (230.6 μg/l for inorganic phosphorus and 4600.4 μg/l for silica). The minimum concentration of inorganic phosphorus (33.5 μg/l), as well as silica (1875.0 μg/l), was observed in March 2016, when the dissolved oxygen content was the highest (3.76 ml/l). The range of observed nutrients content at station 1 was 2725.4 μg/l for silica and 197.2 μg/l for inorganic phosphorus.

The slope of the Gotland Deep (station 5) experienced smaller nutrients content range than the Gdansk Deep – up to 816.7 μg/l for silica and 26.1 μg/l for inorganic phosphorus. The pattern of P and Si content variations was also slightly different. The peak value of nutrients was recorded at station 5 in August 2015 (86.3 μg/l and 2800 μg/l for inorganic phosphorus and silica, correspondingly). While the phosphate content was reduced to the all-period minimum in October (60.1 μg/l), silica minimum was observed in March 2016 (1983 μg/l), when the concentration of inorganic phosphorus showed a slight increase up to 68.8 μg/l.

Another way to know more about aeration difference between the Gdansk Deep and the slope of the Gotland Basin was the investigation of bottom sediments with undisturbed upper layer (0–3 cm) collected by the Niemiste corer in October 2015. The southern slope of the Gotland Basin consisted of oxidized greenish-grey heavily watered aleuritic-pelitic mud. The concentration of Mn in this layer varied from 0.04% at the 3 cm deep to 1.03% in the upper part (0–1 cm), which indicates a good aeration of the upper sediment layer [*Emelyanov,* 2011]. The underlying layer for this was black silt-pelitic silt with the signs of hydrogen sulphide. The collected sediments of the Gdansk Deep were represented by strongly watered black silt-pelitic mud with the signs of hydrogen sulphide. The oxidized layer was absent, thus indications an anaerobic environment. The concentration of Mn in the 0–1 cm layer was 0.04%, which corresponds to the data [*Emelyanov,* 1986, 2017] on the sediments of the deep part of the Gdansk Basin.

The difference in the aeration conditions in the Gdansk Basin and on the slope of the Gotland Basin is also well illustrated by the distribution of zoobenthic communities. According to the October 2015 data, a macro- and meiofauna was present at the southern slope of the Gotland Basin to a depth of 110 m, meaning aerobic conditions at these depths. The total biomass of zoobenthos was low (0.12–3.75 g/m^2), the average abundance was 267 specimens/m^2 (range 16–700 specimens/m^2). The juveniles of the *Macoma balthica* were found, as well as a lot of dead, but strong, undisturbed and blackened shells of this mollusk, at least one year old.

Two species of polychaetes dominated the southern slope of the Gotland deep at depths of 100–110 m: *Scoloplos armiger* (Orbiniidae) and *Bylgides (Antinoella) sarsi* (Polynoidae). These species, as well as *Halicryptus spinulosus* and few meiobenthic ostracods, are tolerant to low oxygen content. The polychaetes *S.armiger* and *B.sarsi* are indicators of the low content of dissolved oxygen in bottom water layers and are the last of the macrofauna to disappear when anoxic conditions occur, and first to appear in the phase of recolonization of previously lifeless areas in the Baltic Sea. These macrobenthic polychaetes are able to exist at an oxygen concentration close to 1 ml/l [*Laine,* 2003; *Olenin,* 1997].

At the same time, both the macrofauna and the meiofauna were absent at the bottom of the Gdansk Basin (103 m). Signs of life on the slope of the Gdansk Basin during this period were observed only from 96 m depth and above. The same two species of polychaetes, *S.armiger* and *B.sarsi*, were found, but macrobenthic organisms were found in much less amounts (the abundance was 124 specimens/m^2; biomass was 0.28 g/m^2) and not in each sample.

Conclusions

The thermohaline parameters of the bottom waters in the southeastern part of the Baltic Sea have undergone significant changes during the 2015–2016, comparing to the mean annual values. In particular, the salinity level at the 100 m depth in the Gdansk Basin increased by 1.5–2 PSU (11.5–17.7%), and the temperature by 1–1.4°C (22.9–28.7%). On the southern slope of the Gotland

Basin, these parameters increased by 0.3–1.27 PSU (2.7–1.4%) and 0.8–1.46°C (17.5–29.2%) respectively. A sharp increase in the main hydrological parameters in the bottom layer of both basins and their subsequent slow decline indicates the water transport from the western Baltic regions and their further assimilation.

The influence of the inflow events at different stations varied. Thus, in the southern part of the Gotland Basin (station 5), the increase in temperature and salinity was less pronounced than in the Gdansk Deep (station 1). The concentrations of dissolved oxygen in the bottom layer of the slope of the Gotland Basin in most cases (except for the spring 2016) exceeded the values observed at station 1 by 0.3–1.0 ml/l. Also, during two surveys (in August and October 2015), oxygen values of less than 1 ml/l were recorded in the Gdansk Basin.

Such anaerobic periods lead to the absence of benthic macro- and meiofauna in the Gdansk Basin. There was no oxidized layer in bottom sediments, and the smell of hydrogen sulfide occurred. The oxidized aleuritic-pelitic mud was collected on the slope of the Gotland Basin, while benthic communities consisted both of the tolerant to a low oxygen content species, of an alive young *Macoma balthica*. These mollusks could slide from overlying slope sections since adult makoms were present only in taphocoenosis. The one-year-old shells indicate that oxygen conditions existed there for about a year. Later, the content of dissolved oxygen decreased, which led to the loss of mollusks from the bottom community.

The observed concentrations of nutrients in the Gdansk Basin were significantly higher, an average of 973 μg/l and 56 μg/l for silicon and phosphorus, respectively. The range of concentration variability at station 1 also exceeded the range of values at station 5 by 3.3 times for dissolved silica and by 7.5 times for inorganic phosphorus.

Thus, the variability of the inorganic phosphorus and dissolved silica content, as well as the distribution of the macrobenthos within the southern slope of the Gotland Basin under conditions of constant dissolved oxygen presence in the bottom layer, is determined mostly by changes in the hydrochemical elements transport conditions and depend on the hydrodynamic activity within the southern slope of the Basin. At the same time, in the Gdansk Basin the content of nutrients and dissolved oxygen and the presence of benthic communities demonstrate a strong dependence on the bottom layer aeration.

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