

Dynamics of Hypoxic Zones in the Baltic Sea in the Late XX–Early XXI Century

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Abstract—The data of shipboard measurements of oxygen concentration at international monitoring stations in the Baltic Sea were used to assess the year-to-year variations of oxygen regime in the late XX–early XXI century (1989–2017). The obtained results were compared with similar studies in 1951–1988. The water areas with hypoxic conditions were found to increase as well as their vertical development. The deterioration of oxygen regime was most considerable in the Gulf of Finland. While in the previous 30 years (1959–1988), hypoxic conditions were recorded only in the western part of the gulf and not in all years, since 1993, hypoxic zones were recorded here every year, developing eastward and appearing more and more often in its central and eastern parts. The analysis of variations of temperature and salinity revealed an increase in the difference between seawater densities in the surface and bottom layers of the Baltic Sea. An assumption was made that the deterioration of the oxygen regime in the Baltic Sea in the recent decades could be due to a stronger stratification of sea water masses.

Keywords: the Baltic Sea, hypoxic conditions, year-to-year variations, quantile analysis, stratification

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INTRODUCTION

Hypoxic conditions in natural waters are diagnosed when its content of dissolved oxygen (O_2) falls below 2 mL/L, resulting in the death of water inhabitants [2]. Such conditions will form because of eutrophication of a water basin—anthropogenic or natural enrichment of water medium by nutrients, leading to an increase in the biological production of the water area. Eutrophication of a water body causes alga blooming, which hampers the photosynthesis of plants in water mass, resulting in their decay, settling onto the bed, thus increasing the amount of organic matter and, accordingly, the consumption of oxygen for its oxidation. The result is an even greater increase in the area of hypoxic zones, denitrification, and release of inorganic phosphorus [12]. As the accumulation of organic matter on the bed reaches a critical level, anaerobic conditions will form, which are favorable for hydrogen sulfide formation. The main condition for the formation of anaerobic zones in the sea, according to estimates of O.A. Alekhin and Yu.I. Lyakhin [1] is the rate of O_2 consumption for biochemical oxidation of organic matter in excess of the rate of its input at weak vertical water circulation and high primary production.

The specific features of O_2 regime formation in the Baltic Sea are associated with a complex of physio-

graphic, hydrodynamic, and biochemical factors, which govern the input, transport and transformation of matter in the sea. The most significant among them are limited water exchange with the North Sea, continental runoff, high anthropogenic load, oxygen absorption from the atmosphere, and its advection and turbulent diffusion in water mass [2].

The results of studying the oxygen regime of Baltic Sea water based on shipboard measurements in the late XX century (1958–1988) are given in [2, 5–7]. The analysis of these results shows that this 30-year period contained time intervals when the Baltic Sea showed no zones of hydrogen-sulfide pollution (1964–1965) or when such pollution was recorded in relatively small water areas in the sea (1967, 1973, 1974, 1977). Since 1968 to 1972 and since 1980 to 1984, the areas of hydrogen-sulfide pollution in the Baltic Sea were largest, and in 1969, 1970, 1972, and 1980, they were recorded even in the western part of the Gulf of Finland, a feature that was not observed in other years. The authors of this study attribute such changes mostly to the changing conditions of advection of North Sea water and changes in the rate of vertical mixing [2].

In the recent twenty years, the joint efforts of the governments of the Baltic states and the activity of the Helsinki Commission succeeded in decreasing the

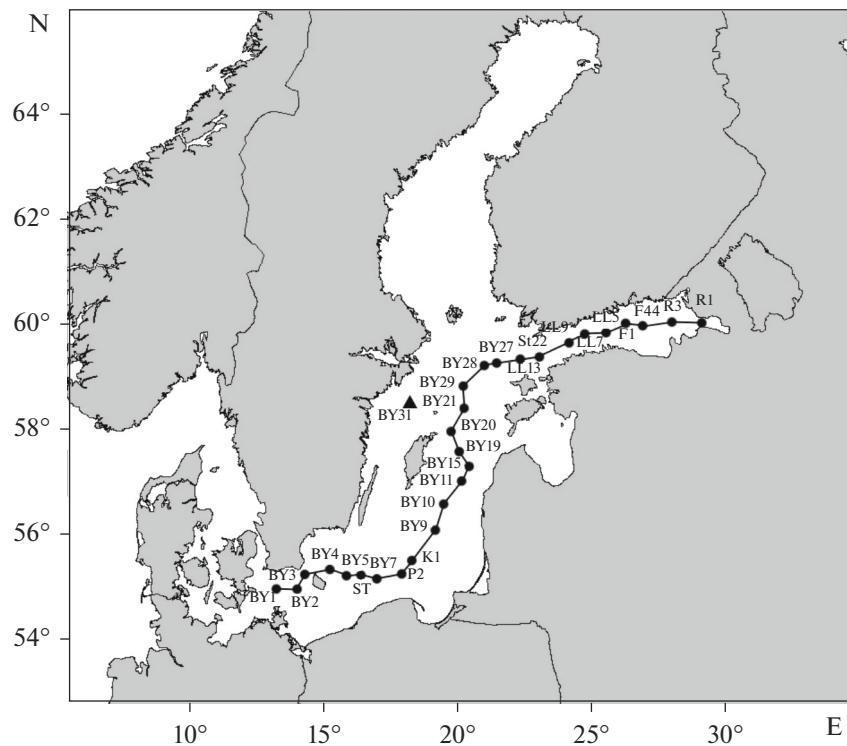


Fig. 1. Layout of the section crossing the Baltic Sea from SW to NE. The circles are the oceanographic stations of the section. The triangle is the position of station BY31.

biogenic load onto Baltic water due to the effluents from agricultural and industrial enterprises and utility sources; however, the concentrations of nutrients in the water are still high [4, 10], and in the period under consideration no decrease in the eutrophication level of the Baltic Sea was observed [11].

To elucidate the causes of the deterioration of the environmental state of the Baltic, Kahru et al. [8] evaluated the correlation between changes in the annual areas occupied by blue-green algae and 29 predictors, including changes in the areas of hypoxic zones, various characteristics of temperature regime on sea surface, the salinity of the surface sea layer, direct and scattered short-wave radiation in July and August, wind speed, the concentrations of major nutrients, and the duration of sunshine in July and August. Neither of the above predictors shows significant correlation with the areas. Kahru with coauthors came to the conclusion that a plausible explanation to the wide year-to-year variations of the frequency of appearance of surface accumulations of cyanobacteria observed in the Baltic Sea is still to be found; however, in their opinion, such variations are most likely due to biological processes [8]. Therefore, the causes of cyanobacterial blooms, accompanied by an increase in hypoxic zones, are not fully understood.

The objective of this study is to assess the changes in hypoxic conditions in the Baltic Sea in the late XX and early XXI century, to compare the obtained results

with estimates of the oxygen regime made in the late XX century, and to discuss the possible causes of the current changes in the hypoxic conditions in the Baltic.

MATERIALS AND METHODS

This study used data of shipboard measurements of O_2 concentration since 1989 to 2017, as well as water temperature and salinity in the Baltic Sea since 1979 to 2017, which have been taken from the international database DAS. The entire data array collected at the stations at which O_2 concentration in Baltic water had been measured was divided into annual massifs to study year-to-year variations in the distributions of hypoxic conditions. If some station showed hypoxic conditions (O_2 concentration < 2 mL/L) at one or several horizons within a year, this site was marked by a black circle, otherwise (if $O_2 \geq 2$ mL/L) it was marked by a gray circle.

To assess the vertical distribution of hypoxic conditions, variation of O_2 concentration over depth was evaluated in each year in a section crossing the Baltic Sea from SW to NE (Fig. 1).

Data on O_2 concentration were collected every year at each station (within 5 km from the station) in a section for standard horizons. The collected data were averaged at standard horizons over year. Next, vertical

distributions of normal annual O₂ concentrations were averaged for each year and for all stations.

To assess the vertical displacements of the upper boundary of hypoxic zone at stations in the section, quantile analysis of the source values of oxygen concentration was carried out for the series with most complete measurement data. Five quantiles were calculated: x_{\min} , $x_{0.25}$, $x_{0.5}$, $x_{0.75}$, x_{\max} (x_{\min} , x_{\max} are the extreme terms of the series x_i , $i = 1, n$; n is the number of the terms in the series, $x_{0.5}$ is the median (Me)):

$$\text{Me} = \begin{cases} x_{(n+1)/2} & \text{for odd } n \\ 0.5 (x_{n/2} + x_{n/2+1}) & \text{for even } n, \end{cases}$$

$x_{0.25}$, $x_{0.75}$ are the medians of the left and right halves of the ranked series.

To study time variations of Baltic Sea water stratification at three stations with widest data available (BY2, BY15, BY31), series of normal monthly values of the temperature (T , °C), salinity (S , ‰), and density (ρ , kg/m³) were constructed for the sea surface and bottom layers. The obtained series were used to evaluate the vertical differences ΔT , °C, ΔS , ‰, and $\Delta \rho$, kg/m³, between the bottom and surface layers.

RESULTS

Figure 2 shows the layout of oceanological stations in individual years in which hypoxic conditions (black circles) in the Baltic Sea in 1989–2017 were marked. It can be seen that the areas of hypoxic zones in this period is greater than it was in the previous 30 years [2, 5–7]. For example, in 1959–1988, hypoxic conditions in the Slupskii Channel, connecting the Bornholm Basin and Gdansk Depression, were observed only in 1968, while at the boundary between the Gulf of Bothnia and the open Baltic Sea, it has never been seen [2]; whereas in the period under study, unfavorable oxygen conditions were recorded in these areas in most cases (Fig. 2).

The deterioration of oxygen regime is most noticeable in the Gulf of Finland. In the previous 30 years (1959–1988), hypoxic conditions were observed only in the extreme western part of the bay and not in all years; while since 1993, they occurred every year, propagating gradually eastward and appearing with increasing frequency in the central and eastern parts of the gulf (Fig. 2).

The Gulf of Riga shows alternation of the periods of the presence and absence of hypoxic zones. The longest period of the absence of the cases of hypoxic conditions here lasted for 4 years (since 1990 to 1993), and, conversely, the longest periods when the Gulf of Riga showed hypoxic conditions were 7 years (since 2002 to 2008) and 5 years long (since 2012 to 2016).

Figure 3 shows year-to-year variations of oxygen conditions in the section crossing the Baltic Sea.

Since 1990 to 1997, oxygen conditions improved at stations in the section in the open part of the sea as can be seen from an increase in oxygen concentration in the top quasihomogeneous layer up to 9–11 mL/L and in deepening of the upper boundary of hypoxic zone in the central Baltic Sea, as well as in disappearing of hypoxic conditions at most stations in the southern and southwestern parts of the sea. The oxygen conditions in this period were most favorable in the northern part of the open Baltic Sea, where the upper boundary of the hypoxic layer in some years dipped to 140–150 m (stations BY28, BY29). After 1997, oxygen conditions in the open Baltic Sea started deteriorating, a tendency, which has persisted up to now. This can be seen from a decrease in O₂ concentration in the surface layer and a steady rise of the upper boundary of the hypoxic layer, which has reached 80–70 m in the recent years. For example, in the mid-1990s in the southwestern part of the sea (st. BY2), the normal annual O₂ concentrations reached 8.3–8.7 in the surface layer, 8.4–8.8 in the central part of the open Baltic Sea (BY15), and 8.5–10.1 mg/L in the western Gulf of Finland (LL9), while in 2015–2017, these estimates decreased to 7.5–7.6, 7.6–7.7, and 7.4–7.5 mg/L, respectively.

Quantile analysis of the vertical displacements of the hypoxic layer upper boundary shows that the median value (Me) of the depth to this boundary in the Southwestern Baltic Sea is 45 m in the Arkonskii basin and 62–72 m in the Bornholm basin (Fig. 4). In the Central Baltic, the Me value of the upper boundary of hypoxia corresponds to larger depths (78–89 m). In the Gulf of Finland, Me corresponds to depth of 59–70 m. The values of x_{\min} in depressions in the open Baltic correspond to the depths of bottom horizons. This is due to the fact that, after the cases of considerable Baltic water inflow, relatively short-time aeration of bottom water takes place, during which the hypoxic conditions disappear. For example, according to estimates of M. Meier et al. [9], the hypoxic conditions in the bottom layer of the Gotland depression after the three recent cases of water inflow disappeared for a period of 1–6 months. Estimates of x_{\max} show that maximal rises of the upper boundary of the hypoxic zone reach depths of 40–50 m in the Gulf of Finland, 40–60 m in the southwestern Baltic Sea, and 50–65 m in the open Baltic Sea.

Figure 5 shows variations of water temperature and salinity in the surface and bottom layers of three oceanographic stations in the period from 1979 to 2017 in the open Baltic, and Fig. 6 gives the vertical differences of water temperature, salinity, and density between the surface and bottom layers at those stations. Water temperature in both the surface and bottom layer increases, while the tendencies in the surface and near-bottom salinity are opposite: it decreases in the surface and increases in the bottom layer (Fig. 6). As can be clearly seen, the increase in salinity in the

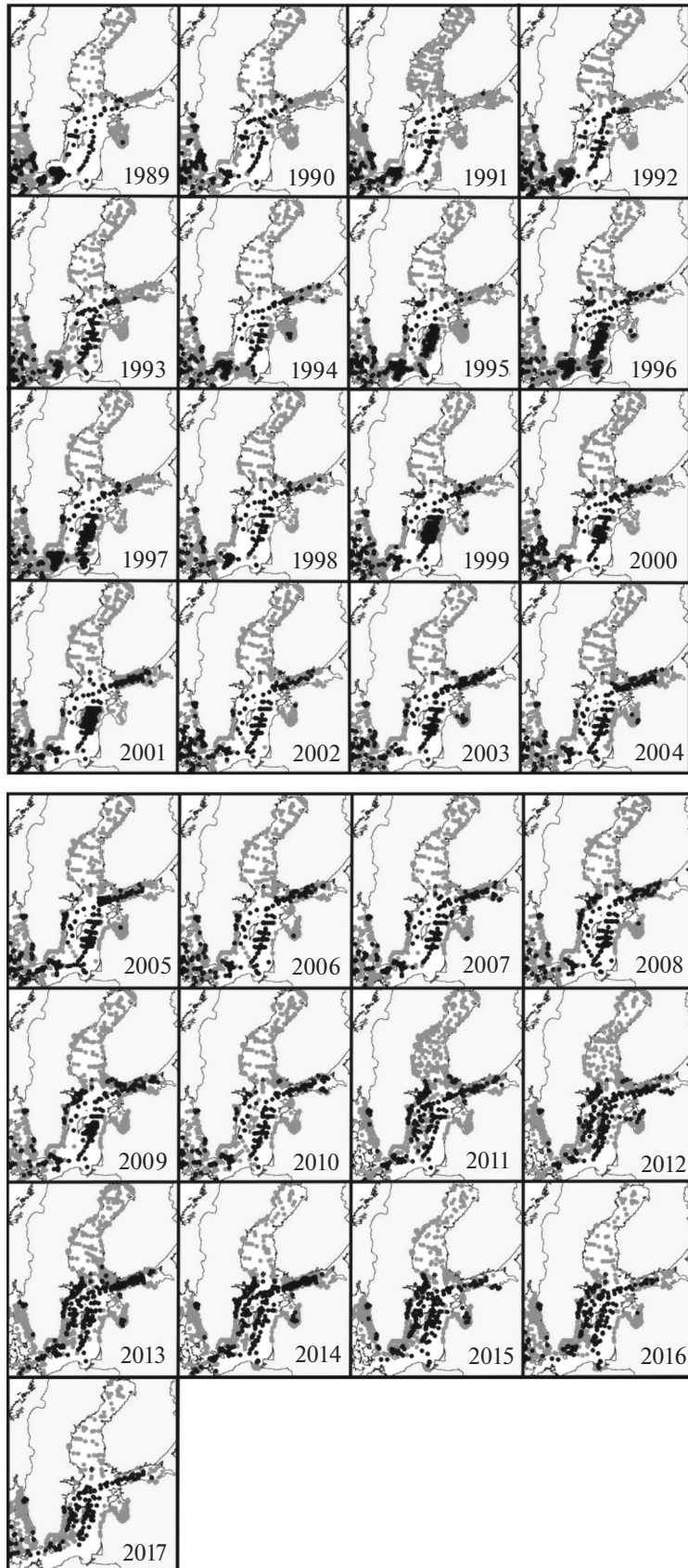


Fig. 2. Layout of the oceanological stations in the Baltic Sea at which hypoxic conditions were (black circles) and were not found (grey circles).

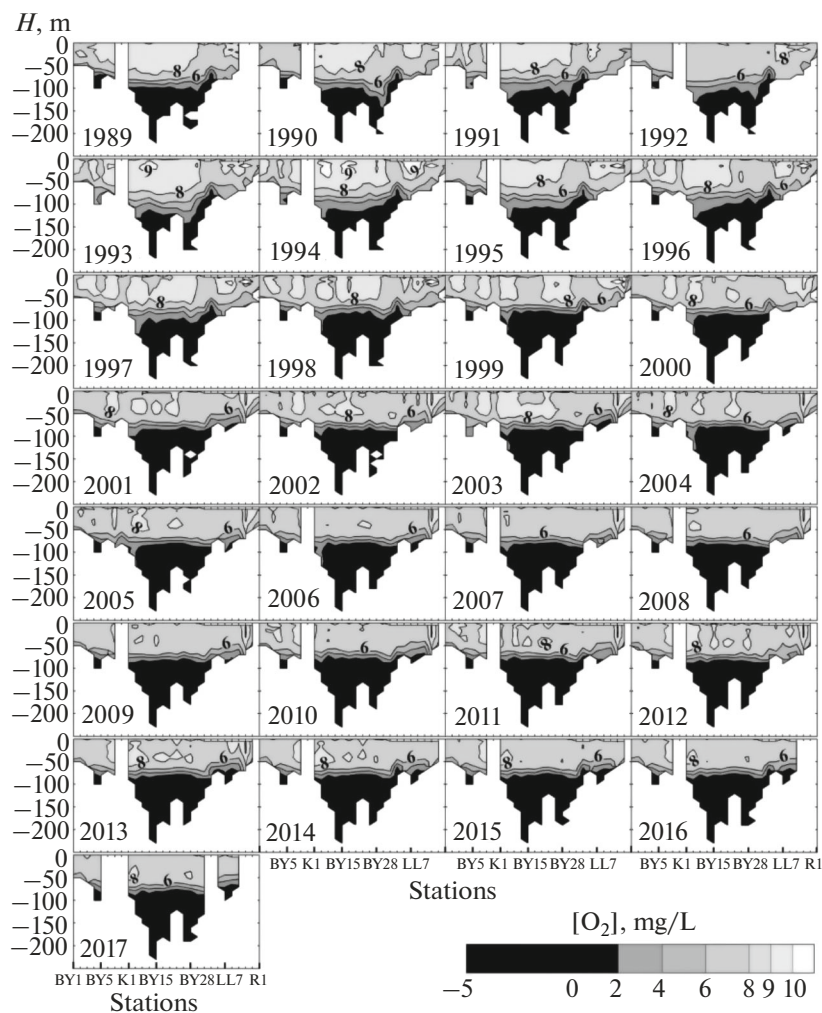


Fig. 3. Vertical distribution of dissolved O₂ concentration in Baltic Sea water at the section of oceanological stations. The black color shows hypoxic conditions.

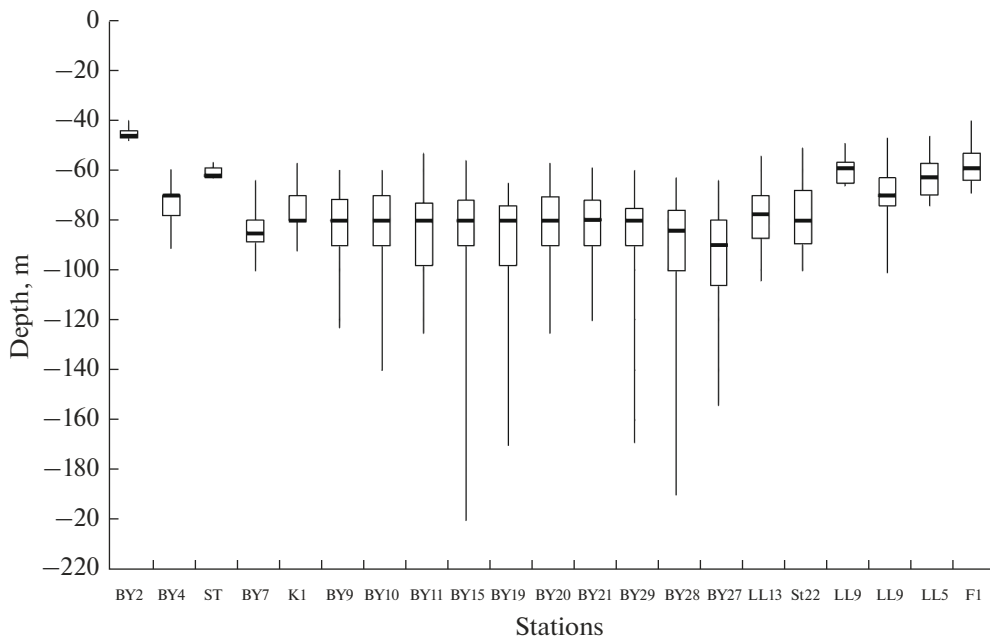


Fig. 4. Quantile characteristics of the vertical displacement of hypoxic layer upper boundary at stations in the section of the Baltic Sea.

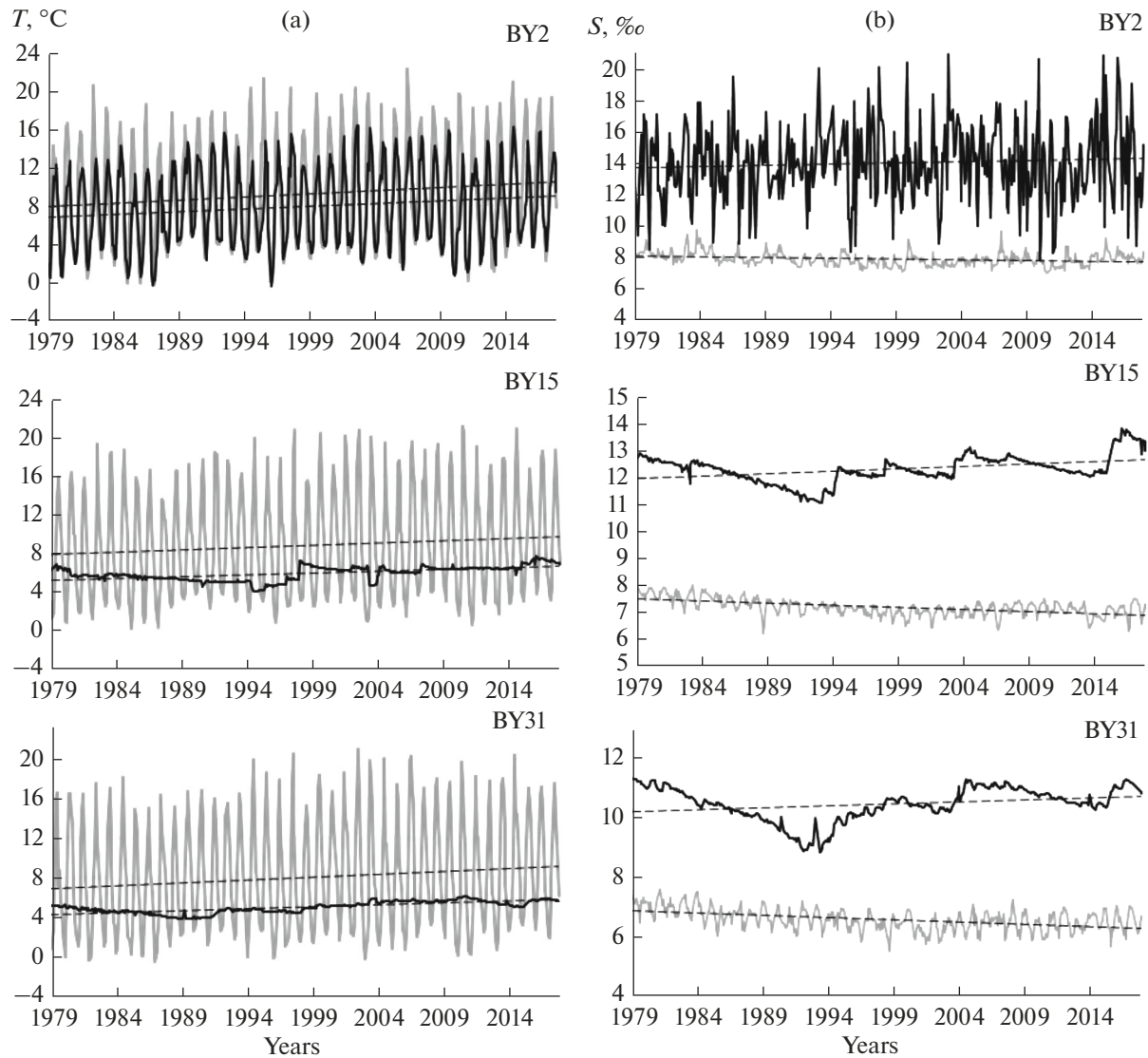


Fig. 5. Variations in the mean monthly values of water (a) temperature T and (b) salinity S in 0–5 m layer (gray line) and deep layer (black line) at stations BY2, BY15, and BY31. The dashed line shows the linear trend.

bottom layers of deep-water depressions (stations BY15 and BY31) is step-wise or wave-like rather than monotonic. Until 1993, water salinity was decreasing at the bed faster than it was doing near the surface, while after that, the bottom salinity started increasing. As can be seen from Figure 6, water stratification increased in all three regions of the open Baltic, mostly because of an increase in the vertical salinity gradient. This can be seen from an increase in the density difference between the surface and bottom layers in linear trends since 1979 to 2017, which range from 0.7 kg/m^3 at station BY2 to 1.1 kg/m^3 at station BY15.

The authors' estimates also show an increase in stratification in the recent decades in different parts of the Gulf of Finland [3], where the analogous trend estimates of an increase in density differences since

1988 to 2014 ranged from 0.5 kg/m^3 in the western to 1.1 kg/m^3 in the central part of the gulf. It is clear that an increase in stratification leads to weaker vertical turbulent diffusion of the substance; this has an adverse effect on the vertical exchange of O_2 between the surface, deep, and bottom layers of Baltic water. It cannot be excluded that these changes in stratification can be among the causes of the deterioration of the oxygen regime of the Baltic Sea.

CONCLUSIONS

The data of shipboard measurements of the concentration of dissolved O_2 at stations of international monitoring in 1989–2017 show that the oxygen regime of both the Baltic Sea as a whole and its individual

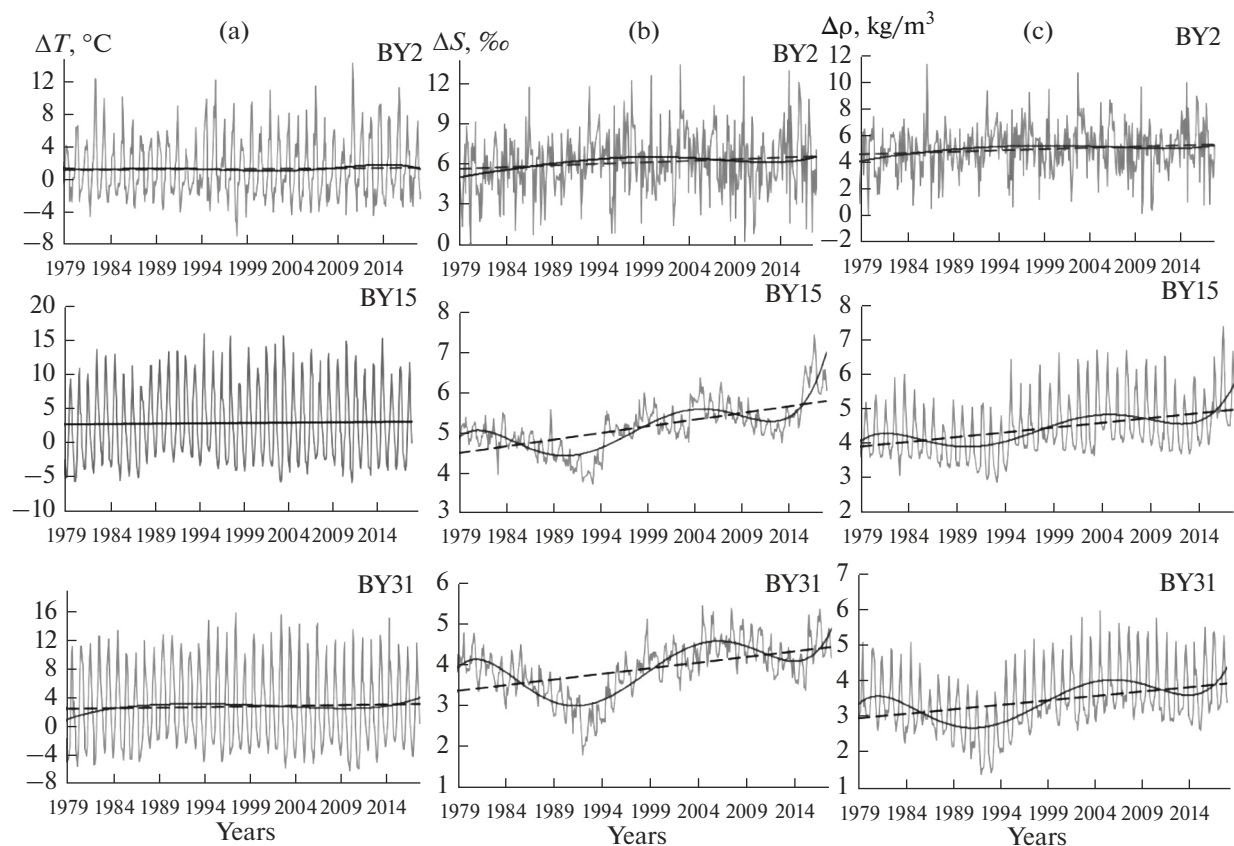


Fig. 6. Vertical gradients of water (a) temperature ΔT , (b) salinity ΔS , and (c) density $\Delta \rho$, calculated for stations BY2, BY15, and BY31. The dashed line shows a linear trend, and the full black line, polynomial trend.

water areas has deteriorated appreciably compared with the previous thirty years. This manifests itself in the increase in the area of hypoxic zones, the decrease in O_2 concentration in the upper quasi-homogeneous layer, and the steady rise of the upper boundary of the hypoxic layer in the open Baltic Sea from the depths of 110–150 m in 1990–1997 to 70–80 m in the recent years. The adverse changes in oxygen conditions are most pronounced in the Gulf of Finland. In the previous thirty years (1959–1988), hypoxic conditions were recorded only in some years in the west-most part of the gulf, while since 1993, hypoxic zones were recorded every year and they appeared more and more often in the central and eastern parts of the Gulf of Finland. The deterioration of the oxygen regime of the Baltic is taking place against the background of considerable changes in the thermohaline structure of its water masses. The analysis of long-term variations of water temperature and salinity in the open part of the Baltic Sea indicates to a rise of the temperature in the surface and bottom layers of the sea, a decrease in the salinity of the surface layer, and its increase at the bed. The identified differences in the thermohaline structure are associated with an increase in stratification of Baltic water masses, primarily, because of an increase

in the vertical salinity gradient. This can be seen in an increase in the density difference in linear trends since 1979 to 2017 between the surface and bottom layers. The increase in stratification can be among the causes of the deterioration of the oxygen regime of the Baltic Sea in the recent decade.

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