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MARINE CHEMISTRY

Study of Dissolved Oxygen Content in the Eastern Bosporus Strait (Peter the Great Bay, Sea of Japan)

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Abstract—Seasonal changes in the dissolved oxygen (DO) content in water were analyzed based on long-term observations (2006–2013) in the Eastern Bosporus Strait (Peter the Great Bay, Sea of Japan). It was found that the monthly average DO concentrations at the bottom of the strait were significantly lower in summer than the average annual long-term data. The minimum DO contents were recorded during four months, from July to October. It was shown that the DO content in water depended on changes in current directions in the strait: lower DO contents resulted from hypoxic water inflow, mostly from Amur Bay.

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The dissolved oxygen (DO) content in water (O_2) characterizes the degree of aeration of the waterbody and is important for estimating its ecological and sanitary state [5, 25, 26]. Variation in O_2 concentrations depends on the level of anthropogenic impact and natural factors, such as the water dynamics, mixing, and exchange with the atmosphere. The state of water in Peter the Great Bay is significantly affected by domestic and industrial wastewater from Vladivostok [10, 14]; according to Roshydromet Survey data [9], its influence is very strong and may significantly decrease the O_2 content.

The minimum DO contents (below 2.5–3.0 mL/L) have been recorded in waters surrounding an urban area (Zolotoi Rog and Amur bays) since 1972 [13, 27], which is explained by a decrease in the intensity of periodic mixing of water [18]. These phenomena have been constant since 1990 [16, 19]. Later, areas of bottom hypoxia in Amur Bay became larger [6, 19, 20], and due to the character of currents [22], they had an impact on the southern parts of Peter the Great Bay. However, transport and transformation of hypoxic waters have been not studied further.

We monitored the state of coastal marine ecosystems in relation to construction of a marine aquarium, which made it possible to obtain a huge hydrochemical dataset on seawater washing Russian Island, in particular, its northern part, the Eastern Bosporus Strait. Being oriented in various directions and connected to secondary bays (Amur and Ussuri), this is the northernmost strait system dividing a group of large islands in Peter the Great Bay (Fig. 1). It has a length of ~9 km and widths of 0.8, 1.5, and 3.7 km in the central, western, and eastern parts, respectively. The main depths along the axial line are 28–36 m. A trough with a maximum depth of 50 m occurs in the western part. Zolotoi Rog, Diomid, Uliss, and Patrokl bays are located on the northern coast; Ayaks and Paris bays, on the southern coast.

Our goals are to study the concentration of DO in water of the Eastern Bosporus Strait, shallow bays in the northern part of the Russian Island and to estimate the role of natural factors in the formation of its intraseasonal dynamics based on observations in recent years (2006–2013).

MATERIAL AND METHODS

Our study was based on the materials collected from 2006 to 2013 with involvement of archival data of expeditions of the Ilyichev Pacific Oceanological Institute, Far East Branch, Russian Academy of Sciences [21]; the Far East Regional Hydrometeorological Research Institute [1, 11, 16]; and N. Khristoforova [23].

Sample were collected and analyzed out by standard techniques. Chemical analyses of the DO concentration were performed in accordance with regulatory Roshydromet documents (URL: http://www.snti.ru/spr.php). Some samples were analyzed at the certified laboratory of the Pollution Monitoring Center, Primorye Administration for Hydrometeorology and Environmental Monitoring; others were analyzed at the certified EKOANALYTIKA laboratory under contract with the Zhirmunsky Institute of Marine

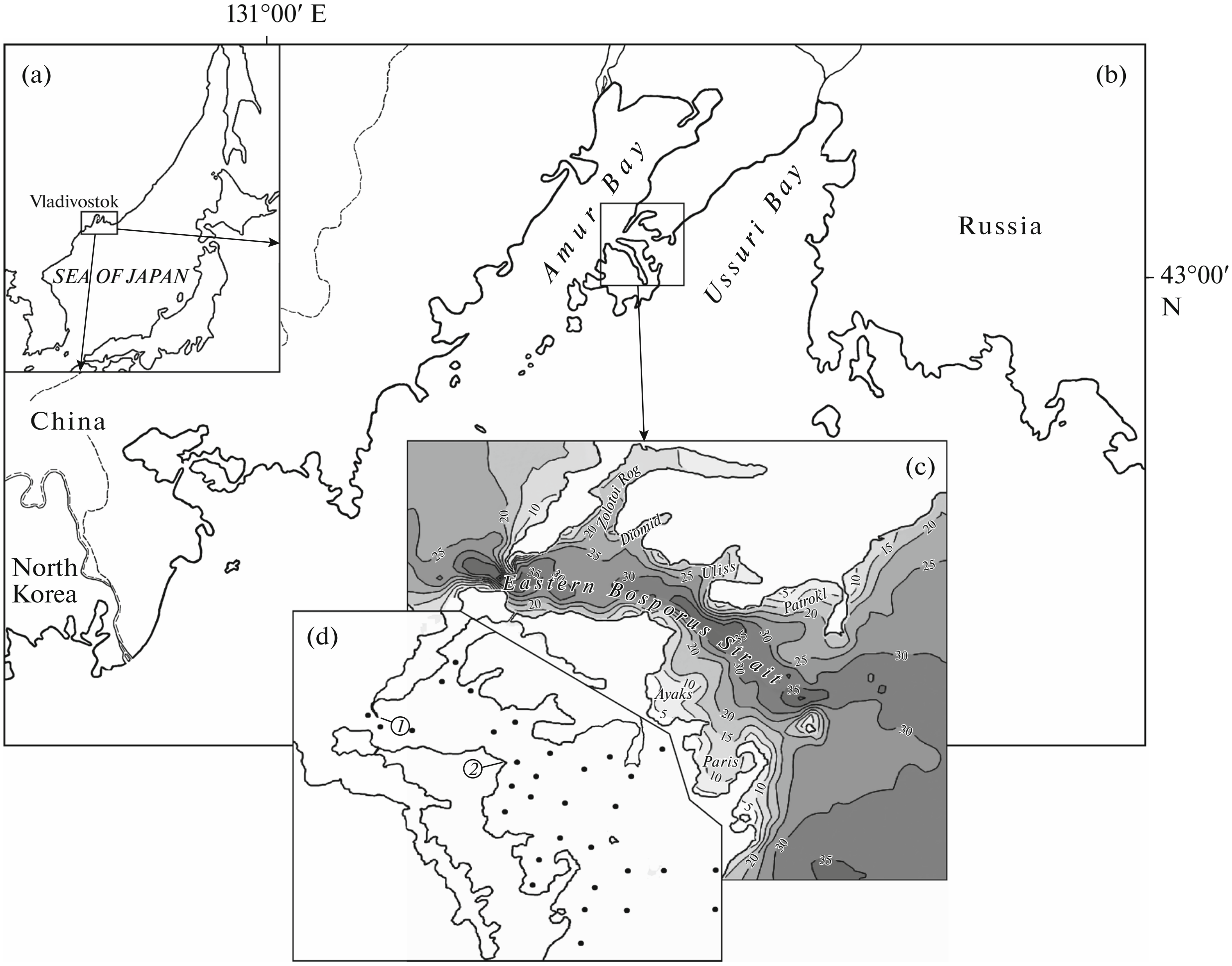

Fig. 1. Maps of studied area (a), Peter the Great Bay (b), Eastern Bosporus Strait (c), and scheme of water sampling stations (d). (*1*) Cape Tokarevskaya Koshka (Tokarevskii lighthouse); (*2*) Cape Novosil'skii.

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In this study, we used data from different networks, comprising 33 stations including the adjacent water area of Ussuri Bay. Average monthly values were calculated for a station in the western part of the strait, from Cape Tokarevskaya Koshka (Tokarevskii lighthouse) to Cape Novosil'skii and the bays of Ayaks and Patrokl; the reliability of the mean difference was verified by Student's *t*-criterion. All calculations were performed in Excel; the parameter distributions were interpreted in graph form using Surfer software by the kriging method [8].

RESULTS AND DISCUSSION

It is known that the DO content in the surface water layer of the Peter the Great Bay has seasonal variations with a maximum in the cold period and minimum in summer [2, 13]. The first extremum results from the low water temperature and extensive formation of phytoplankton. The second extremum is explained by high temperatures and intense bacterial destruction processes. The mean annual DO content in the surface water layer of Peter the Great Bay is within 6–8 mL/L, 100–120% saturation; in the bottom layer, from 4 to 6 mL/L, 50–80% saturation [16]. The most significant variations in O_2 content are observed in the period of spring–summer heating of water. In spring, the DO contents in the surface layer can reach 9–10 mL/L in Ussuri and Amur bays and 12 mL/L in Zolotoi Rog Bay, 90–130% saturation; in summer, they decrease to 4–5 mL/L, 45–90% saturation.

The concentration of DO in surface waters of the Eastern Bosporus Strait and adjacent bays is quite high, more than 100% saturation, even in summer. As is evident from the data on stations of the Division of the State Observation System [2], the maximum average contents of O_2 are recorded in January–April: 7.7–9.4 mL/L, 101–130% saturation, with an absolute maximum of 9.8 mL/L, 134% saturation (Fig. 2). The lowest mean monthly O_2 concentrations are observed in July–September: 5.0–6.8 mL/L, 90–

127% saturation. The minimum is recorded in September (4.7 mL/L, 84% saturation). At the bottom, these average values are >7.7 mL/L (98% saturation) in the first part of the year and may be similar to those in the surface layer, but in summer they decrease to 3.0–5.5 mL/L, 50–89% saturation. The minimum (2.6 mL/L, 46% saturation) is recorded in September as well.

According to our data (2006–2013), in summer (July–August), the average DO content in the surface water layer of the Eastern Bosporus Strait was almost the same (5.7–5.9 mL/L, 106–111% saturation), but at the bottom the O_2 content decreased significantly: on the average 2.6–3.5 mL/L, 46–59% saturation (Fig. 2). The minimum value (1.16 mL/L, 19% saturation) was recorded in August near Tokarevskaya Koshka Bay (Tokarevskii lighthouse). It should be noted that the decrease in O_2 to 2.5–3.0 mL/L in the bottom layer in summer was recorded in all years of observations, 1.0–2.0 mL/L in 2007, 2011, and 2013. In addition, the first appearance of hypoxic waters in the strait was recorded in October, 2011 and 2012. Thus, we have found that the decrease in DO concentration in the bottom water layer of the Eastern Bosporus Strait to 2.5 mL/L became a common phenomenon, and in some years the O_2 content reached critical values (1.0–2.0 mL/L); as a whole, the minimum O_2 content was recorded over four months (from July to October).

It was also found that in summer and autumn, the average O_2 content in the bottom water layer of the strait was lower in its western part than in the eastern (Table 1). This difference was especially appreciable (on average, by 1–2 mL/L) in August–September (probably in July as well, since our data are incomplete). In September–October, when the DO contents are usually aligned at the bottom, 4.0–5.0 mL/L, the average O_2 contents were lower in the western part of the strait. These differences were also evident from one-shot surveys. For example, in June 2006, the DO content in the bottom water layers (8–24 m) of Diomid, Uliss, Ayaks, and Paris bays was 5.25–5.74 mL/L, whereas at the same depths of Zolotoi Rog Bay and Cape Tokarevskaya Koshka, the O_2 content was 2.22–4.03 mL/L. Similar situations were observed in other studied years. With great confidence, we can say that this difference is explained by the predominant influence of hypoxic waters coming from Amur and Zolotoi Rog bays.

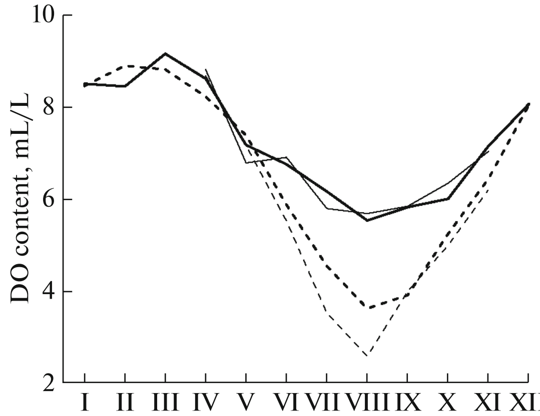

Fig. 2. Average monthly DO content in 1981–1985 (bold line) and in 2006–2013 (common line) at water surface (solid line) and at bottom (dashed line) over course of year in Eastern Bosporus Strait (average values are calculated for stations in western part of strait, from Tokarevskii lighthouse to Ayaks and Patrokl bays).

Natural factors control variations in the DO content in water. These variations result from variation in the synoptic situation, fluctuations in directions of the main currents, mixing, etc. Variations in the O_2 content in water of the Eastern Bosporus Strait show that migration of hypoxic waters through the strait can take place for one month. For example, illustrations from August 15 to September 17, 2007 clearly show waters depleted in oxygen coming from Amur Bay; we can see their localization in some places of the strait, as well as the moment of their removal to Ussuri Bay (Fig. 3). At the same time, this figure clearly shows the water inflow from the deep-water part of Peter the Great Bay to the eastern part of the Eastern Bosporus Strait. Despite passage of hypoxic waters, on some days, the DO content in the bottom horizons in late August is 5.0–6.5 mL/L (Fig. 3). Here we observe two processes: passage of hypoxic waters through the strait and inflow of bottom waters from the deep-water part

Table 1. Average monthly DO concentration (mL/L) in surface layer/at bottom of Eastern Bosporus Strait in 2006–2013

Areas of Eastern Bosporus Strait	Months							
	April	May	June	July	August	September	October	November
Entrance to strait from Amur Bay*	–/–	6.82/7.49	6.50/5.43	5.63/3.67	5.56/2.08	5.30/2.67	5.91/4.56	6.61/5.37
Western part**	8.82/8.68	6.79/7.17	6.91/5.53	5.80/3.53	5.69/2.59	5.85/4.00	6.35/5.00	7.04/6.21
Eastern part***	8.91/8.48	7.13/7.66	6.75/5.23	5.95/–	5.28/4.07	5.70/4.43	6.19/5.12	7.30/6.15

* Entrance to strait: from Cape Tokarevskii (Amur Bay) to Cape Tokarevskaya Koshka; ** western part: from Cape Tokarevskaya Koshka to Cape Novosil'skii and Ayaks and Patrokl bays; *** eastern part: from Cape Novosil'skii to mouth of Ussuri Bay.

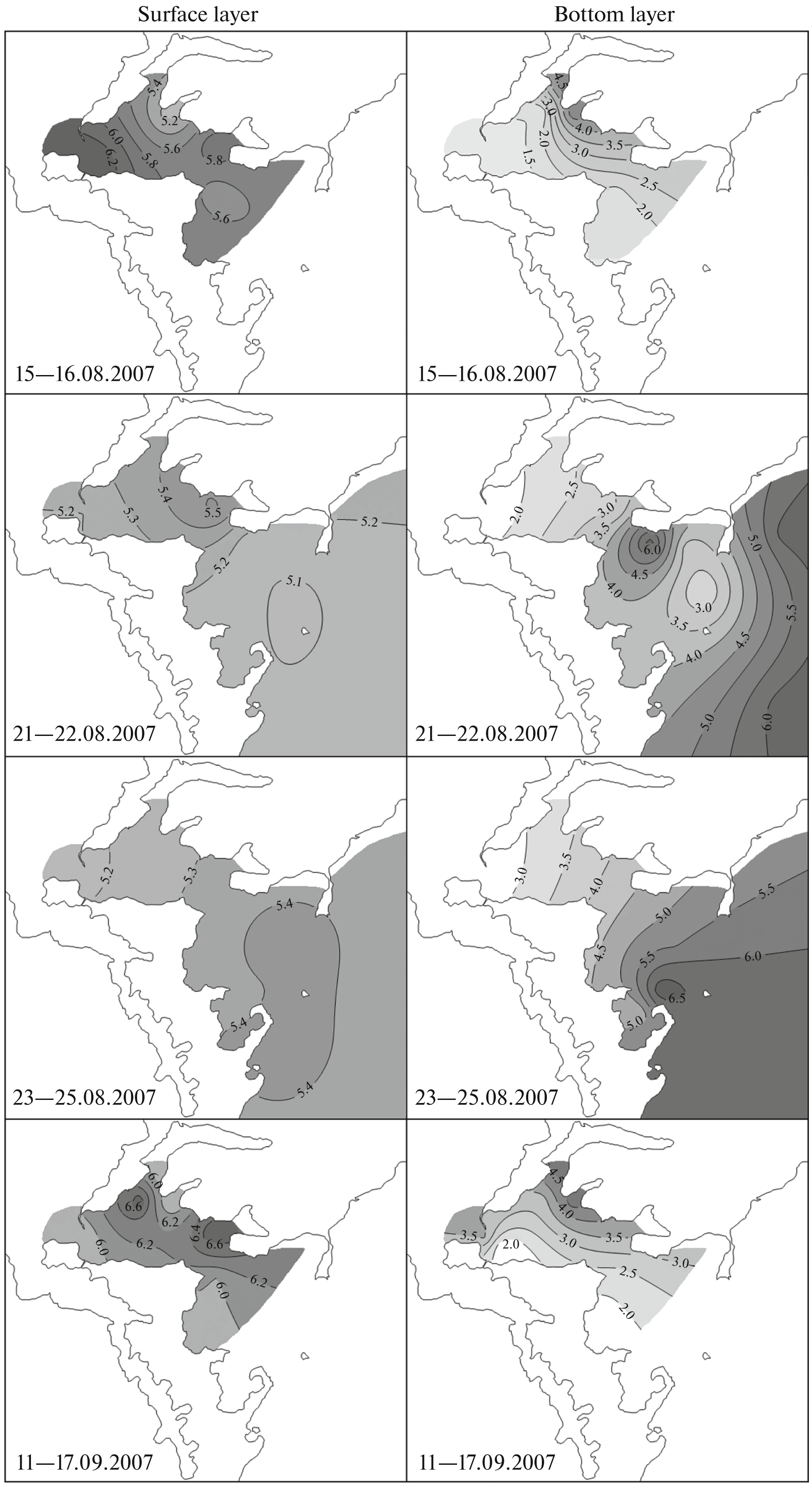

Fig. 3. DO content (mL/L) in Eastern Bosporus Strait and adjacent regions on August 15–16, 21–22, 23–25 and September 11–17, 2007.

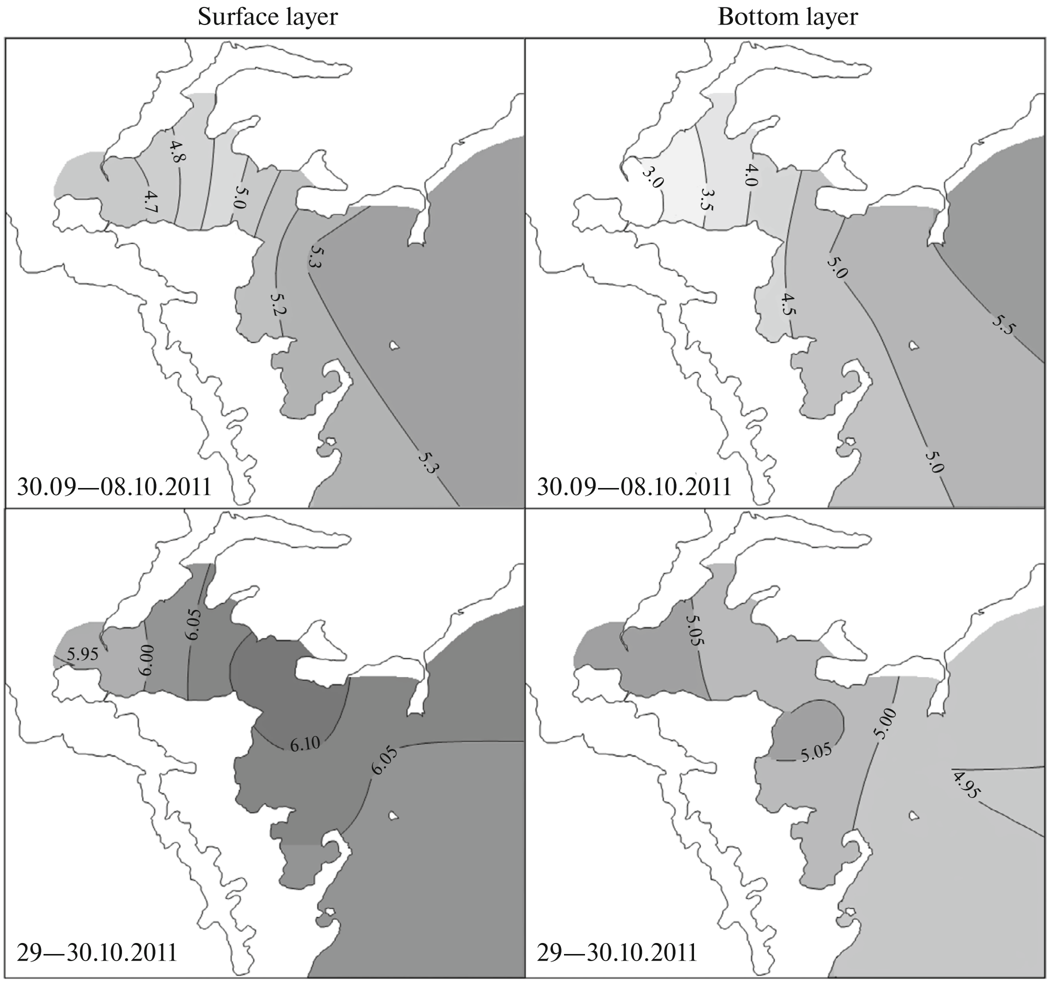

Fig. 4. Content of DO (mL/L) in Eastern Bosporus Strait and adjacent regions on 30.09–8.10 and 29–30.10.2011.

of Peter the Great Bay with constant upwelling in the shelf zone. As is evident from observations, both these processes can interact intensively when the influence of upwelling in the strait becomes predominant, but passage of waters depleted in oxygen from Amur Bay is still appreciable, like in October 2011 (Fig. 4).

According to the literature data [21], in the summer period, waters migrating through the Eastern Bosporus Strait mostly come from the northern part of Amur Bay and are recorded in the bottom layer near the Tokarevskii lighthouse even when southeastern winds predominate in the warm season. Sometimes their influence persists in the bottom layer when there are also northern winds. In June–July of some years, water passage may be significant and can be recorded over the entire water column of the strait; because of this, low DO contents can be observed in water of the western bottom basin of Ussuri Bay in late August [4, 17]. Based on the materials of a multiday station moored near Cape Tokarevskaya Koshka in 2009, hypoxic waters were observed for 1.5 months [7].

According to data of previous studies, the direction of general transport from east to west in the Eastern Bosporus Strait changes in August–September [21]. In September–October, the western stream begins to dominate completely and cool deep waters of Peter the Great Bay penetrate into the Eastern Bosporus Strait and pass to Amur Bay. In the opinion of many researchers [4, 7, 17], upwelling of waters from the Sea of Japan and their further advection into the upper parts of bays in August–October is the main mechanism of water exchange and destruction of summer hypoxia in the bottom layer of Amur Bay. These papers show that rising of waters and migration of marine water masses to the shelf may be undulating in a pulsing mode, as was observed in October 2008 and 2011. The bottom horizons are characterized by sharp jumps in the main hydrological and hydrochemical characteristics of seawater, significantly exceeding their variability compared to the data for surface waters [24]. For example, according to observations in July–September 2007–2009 [15], abrupt changes in temperature (by 15°C) and salinity (by 1‰) were recorded in Ussuri Bay over 5–7 days, which resulted from penetration of submesoscale flows of the anticyclonic gyre to the bay. In addition, as is evident from the materials of V. Budaeva [1], at the beginning of September 2011, signs of early upwelling to the southwestern part of Ussuri Bay were recorded with a decrease in temperature by 1–2°C and increase in water salinity by 0.1–0.2‰.

Analyzing the available materials, we could not detect the exact moments of changes in main water transfer in the Eastern Bosporus Strait during the studied years, mostly due to lack of data, since monitoring was not continuous. In addition, the intensity of transfer is unclear and requires additional studies. We only observed that in Peter the Great Bay, upwelling resumed in July 2008, on August 20 in 2007 and 2009, and at the beginning of September in 2010 and 2011. Thus, as is evident from hydrological survey of data different years, the moment of changes in predominant currents in the Eastern Bosporus Strait varies in different years from the end of July to the end of September, as does the influence on the DO content in water, which reflects interseasonal variability on a regional scale.

CONCLUSIONS

Analysis of the DO content in water of the Eastern Bosporus Strait performed in 2006–2013 showed that in the summer period, the average O_2 concentrations in the surface layer were almost the same, whereas at the bottom, they decreased significantly. The minimum was recorded in August in the western part of the strait. The general decrease in DO content in the bottom water layers of the Eastern Bosporus Strait started in June, and the minimum values were reached in four months, from July to October. Variations in the DO concentrations result from predominance of a particular direction of water transfer in the strait; hypoxic waters are removed from Amur and Zolotoi Rog bays.

Therefore, it is evident that periodic decreases in DO concentrations can threaten the ecosystem of the Eastern Bosporus Strait, although they are not catastrophic in nature. However, many researchers have noted that in recent years, the composition of the bottom community changed significantly in Amur Bay: the species composition became less diverse and the share of zoobenthos species resistant to oxygen deficiency increased [3]. By now, radical changes in benthic biomass subjected to the influence of hypoxia have been recorded [12]. Thus, our new materials on the DO concentration in coastal waters lean toward a pessimistic outlook for the ecological state of the studied bays. We can only hope for their ability to self-purify, which still lends some stability in the preservation of ecosystems. The study was carried out with the partial support of the grant "Far East" no. 15-I-6-059.

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