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PECULIARITIES OF TEMPORAL VARIABILITY OF DISSOLVED OXYGEN CONTENT IN EELGRASS *ZOSTERA MARINA* LINNAEUS, 1753 MEADOWS IN THE VOEVODA BAY (THE AMUR BAY, THE SEA OF JAPAN)

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Currently, the shallow basins with *Zostera marina* L. meadows are considered as absorbers of atmospheric carbon dioxide, capable of restraining an increase in its concentration. Due to its high primary productivity, eelgrass releases a large amount of oxygen into the environment. To establish the peculiarities of production activity in shallow-water basins, covered with *Z. marina* meadows, we conducted monitoring of hydrological and production indicators with different measurement intervals on the example of the Voevoda Bay (the Amur Bay, the Sea of Japan). Observations were carried out for eight and a half months (22.09.2012–07.06.2013). Measurements of temperature, salinity, chlorophyll fluorescence, and turbidity were carried out in *Z. marina* meadows at a depth of 4 m every three hours by a Water Quality Monitor hydrological station. Dissolved oxygen content was determined every hour by an optical oxygen sensor ARO-USB. Two types of oxygen concentration variability were established: 1) seasonal variability, mostly resulting from seasonal variations in the environment; 2) daily variability during the freeze-up period, mostly determined by the intensity of photosynthetically active radiation penetration into sub-ice water. In the autumn season, low oxygen concentrations, up to hypoxic level, were recorded. In the winter and spring seasons, the oxygen content was, as a rule, at 100–130 % of saturation. High daily variability was observed during the freeze-up period, with no snow coverage. In February, the range of daily fluctuations of oxygen concentration reached 730 $\mu\text{mol}\cdot\text{kg}^{-1}$, with 3-fold supersaturation regarding atmospheric O_2. As established, the maximum rate of oxygen production, relative to 1 g of *Z. marina* wet weight, is 6.5 mg $O_2\cdot h^{-1}\cdot g^{-1}$. High daily dynamics of oxygen in seawater is analyzed in relation to eelgrass physiological peculiarities (air lacunae play an important role in oxygen dynamics in the environment), as well as to short-period tides.

Keywords: *Zostera marina* L., macrophytes, dissolved oxygen, Voevoda Bay, Amur Bay, Sea of Japan

To date, there is ample evidence that global changes, such as deoxygenation and acidification, are taking place in the World Ocean (Dore et al., 2009 ; Schmodtko et al., 2017). These changes affect both coastal waters and the open areas of the oceans, and they are explained from different positions.

Most researchers relate global changes in the open ocean to warming, resulting in reducing the oxygen solubility and leading to water stagnation, *i. e.* a decrease in the rate of oxygen transfer from the surface horizons to the deeper ocean layers. Changes in coastal waters are mainly explained by eutrophication (their nutrient enrichment), as well as by an increase in the intensity of production and destruction of organic matter (De Jonge et al., 2002). The acidification of the World Ocean is usually related to an increase in carbon dioxide concentration in the atmosphere (Dore et al., 2009).

Shallow-water basins with *Zostera marina* Linnaeus, 1753 meadows are considered as absorbers of atmospheric carbon dioxide, capable of restraining an increase in its concentration due to eelgrass high productivity (Blue Carbon…, 2009). Obviously, as a result of *Z. marina* photosynthetic activity, not only carbon dioxide is absorbed and organic matter is formed (vegetative and generative shoots and rhizomes), but also oxygen is released into the environment; it is confirmed by direct observations of oxygen production, the gross values of which can reach 2 mg $O_2 \cdot h^{-1}$ per 1 gram of wet weight (Berger, 2011). It was previously established that biogeochemical processes in the Voevoda Bay (the Amur Bay, the Sea of Japan), where eelgrass meadows grow, are determined by the seasonal variability of the production/destruction of organic matter (Barabanshchikov et al., 2015). It was assumed that in the winter season, the intensity of production processes at the bottom is higher than at the surface due to *Z. marina*. The predominance of production activity in the bottom horizons in the winter period causes an increase in oxygen concentration and a decrease in the partial pressure of carbon dioxide at the bottom compared to that of the surface layer waters (Barabanshchikov et al., 2015). It was also found that eelgrass production activity has both seasonal variability and daily one (Kharlamenko et al., 1994).

The aim of this work is to establish the peculiarities of the production activity manifestation of shallow-water basins, covered with *Z. marina* meadows, on the example of the Voevoda Bay, by monitoring hydrological and production indicators with different measurement intervals.

MATERIAL AND METHODS

The Voevoda Bay is located in the eastern seaward area of the Amur Bay (Peter the Great Bay, the Sea of Japan), deeply going into the western coast of Russky Island (Fig. 1).

The Voevoda Bay in its northern area includes the Kruglaya and Melkovodnaya bays. Water area of the Voevoda Bay is about 4 km^2, of the Melkovodnaya Bay – about 2.4 km^2 (Lotsiya severo-zapadnogo…, 1996). The shores, adjacent to the entrance capes of the bays, are elevated and deep; in the inner area, they are low. Off the low-lying shores, the coastal area is shallow; depths of 10 m are usually about 1 km from the coast. The bottom is rocky; off the low-lying shores, it is sandy and sandy-silty. From the east, the Russkaya River flows into the bay; this river is about 6 km long and is fed mainly by rain; the flow rate varies 0.2 to 2.0 $m^3 \cdot s^{-1}$ throughout the year. In the Voevoda Bay, 6 sites were revealed, covered with *Z. marina* meadows, which are located in the upper sublittoral at depths of no more than 10 m and have silty and sandy-silty soils. *Z. marina* meadows are located in calm, wave-protected areas: in the southern shallow waters of the Voevoda, Kruglaya, and Melkovodnaya bays (Fig. 1). The largest areas of eelgrass meadows were registered in the tail-end sites of the Kruglaya and Melkovodnaya bays, with an area of 900×400 m and 1000×500 m, respectively. In this water area, the density of *Z. marina* biomass reaches 3 kg of wet weight per 1 m^2 with a projective cover of 100 %. On average, for the entire Voevoda Bay, eelgrass biomass was of 0.5–1.5 kg of wet weight per 1 m^2 (Barabanshchikov et al., 2018).

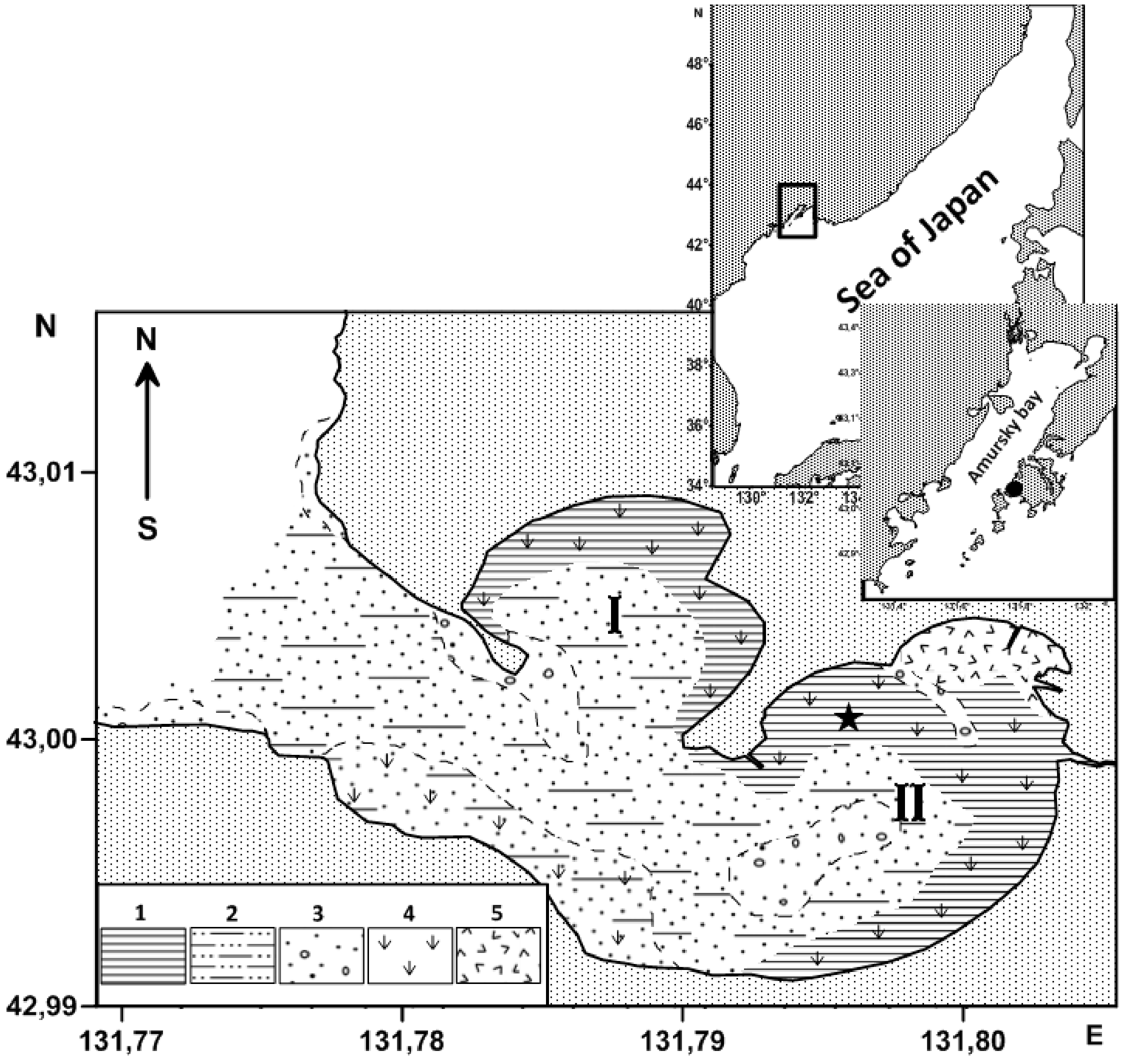

Fig. 1. Map of bottom landscapes and bottom biocenoses in the Voevoda Bay: I – the Kruglaya Bay, II – the Melkovodnaya Bay; 1 – clayey silt; 2 – clayey silt, sandstone; 3 – sand, stone; 4 – *Zostera marina* L. meadows; 5 – oyster *Crassostrea gigas* colony; ★ – Water Quality Monitor hydrological station setting point

A Water Quality Monitor hydrological station (WQM, Wet Labs) was set in the Melkovodnaya Bay (see Fig. 1) at a depth of 4 m for the period 22.09.2012–07.06.2013. The coordinates were 42°59.978′N, 131°47.659′E. The station was equipped with sensors of pressure, temperature, electrical conductivity, chlorophyll fluorescence, and turbidity. The WQM station was equipped with an automatic system for flushing the sensors with a fluid for biofouling destruction and for cleaning the optical windows. At the WQM station, a fast-response optical oxygen sensor ARO-USB (Japan) was installed. Its readings were compared with those obtained by an automated version of the Winkler method (Talley et al., 2004) within the temperature range of +5…+29 °C. The introduced correction depended on temperature; the readings of the oxygen sensor were corrected in accordance with the empirical relation:

$$[O_2]_{cor}(ml \cdot l^{-1}) = [O_2]_{meas} - 1.075 + 0.04 \cdot t\,, \tag{1}$$

where $[O_2]_{cor}$ and $[O_2]_{meas}$ are corrected and measured oxygen concentrations, $mL{\cdot}L^{-1}$;

t is temperature, °C.

When obtaining the relation (1), nine measurements were used; $R^2 = 0.97$.

For eight and a half months, every 3 hours, the readings of the sensors of temperature, salinity, chlorophyll *a* fluorescence, and turbidity were recorded for 5 minutes with an interval of 1 second. The ARO-USB sensor recorded oxygen concentration at 1-hour interval. For each day, the average values of the sensor readings were obtained.

To analyze the results, the intensity (I) of photosynthetically active radiation, falling on the ice surface, was estimated for February 2013. Its value, depending on the season and astronomical characteristics, was calculated for a cloudless sky by the formula:

$$[I] = [I_0] \cdot \sin(h) \,, \tag{2}$$

where h is the Sun height above the horizon;

$[I_0]$ is solar constant when the Sun is at its zenith, $[I_0] \approx 1670\ \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Kirk, 1992).

The Sun height h for the Northern Hemisphere was determined by the basic astronomical formula (Barteneva et al., 1971):

$$sin(h) = cos(\phi) \cdot cos(\delta) \cdot cos(\tau) + sin(\phi) \cdot sin(\delta) \,, \tag{3}$$

where φ is geographic latitude;

δ is declination, $\delta = 23° \times \cos(2\pi \times (N+9)/365)$ (N is the ordinal number of the day of the year, starting from 1 January);

τ is hour angle, $\tau = 2\pi \times t/24$ (t is time of the day, hour).

RESULTS

Seasonal variability of bottom water hydrological indicators of the Voevoda Bay at the WQM station for the period 22.09.2012–07.06.2013, based on the daily average results (Fig. 2), is typical for the latitudes studied.

When setting the station, the bottom water temperature was about +20 °C, and the salinity was about 31.5 ‰. The characteristic features of the autumn season are a decrease in water temperature and significant fluctuations in salinity, caused by coastal freshwater runoff and strong wind mixing of water. From 9 December to 2 April, the bay is covered with ice (this interval is marked with red vertical lines in Fig. 2). During the freeze-up period, there are no small-scale temperature and salinity fluctuations, since there is no wind mixing. Temperature of the bottom water during this period is close to the freezing point. Salinity of the bottom water increases December to early March, reaching 34.20 ‰, which is associated with ice formation. From the beginning of March until the ice cover break-up, a decrease in salinity is observed, resulting from ice melting in the daytime [its salinity is about 6 ‰ (Zvalinsky et al., 2010)] and meltwater inflow through the ice pores into ice water. After the ice cover break-up, a seasonal increase in temperature occurs, as well as a decrease in salinity, accompanied by fluctuations in these indicators due to wind mixing.

The results of measurements of dissolved oxygen content and the saturation degree in the bottom water with the ARO-USB sensor are shown in Fig. 3a and b, respectively. The saturation degree was calculated by the equation, proposed in (Weiss, 1970). The results obtained demonstrate two types of oxygen concentration variability and its saturation degree: 1) long-term variability due to seasonal variations in the environment; 2) short-term (daily) variability. It should be noted that long-term variability in the water saturation degree with oxygen slightly deviate from the state of 100 % of saturation, with the exception of the autumn season and January 2013. Short-term variations are, as a rule, positive deviations regarding the "baseline" of long-term ones. In our case, the "baseline" is of 100–130 % of the oxygen saturation degree (Fig. 3b). The range of these variations can be extremely wide, reaching in some cases 3-fold water supersaturation regarding atmospheric oxygen.

Temporal variability of chlorophyll fluorescence and turbidity (Fig. 3c, d) demonstrates two seasonal peaks: in November and in early April, at the time of ice cover break-up in the bay. The results obtained confirm the fact of spring and autumn phytoplankton bloom, which is typical for the Sea of Japan open water area (Yamada & Ishizaka, 2005) and for its coastal area (Tishchenko et al., 2020a). It should be noted that the autumn phytoplankton bloom did not affect the oxygen content (see Fig. 3). On the contrary, the spring phytoplankton bloom caused positive fluctuations in the O_2 concentration. This phenomenon was accompanied by a high turbidity (see Fig. 3d), which was obviously caused by the inflow of aerosol, accumulated on the ice surface in the winter season, during the period of ice cover break-up and its intensive melting.

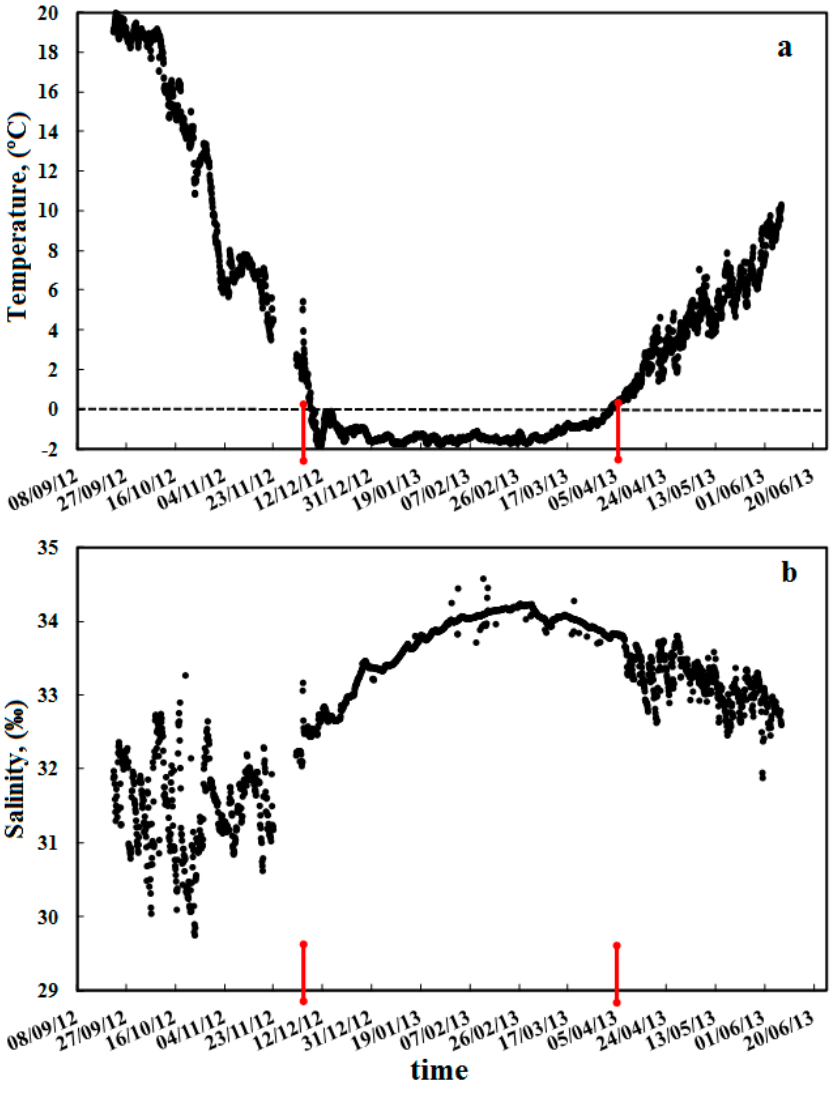

Fig. 2. Temporal variability of indicators (a – temperature, °C; b – salinity, ‰) in the bottom water of the Voevoda Bay on 22.09.2012–07.06.2013 at WQM hydrological station (42°59.978′N, 131°47.659′E). Red lines mark the freeze-up period

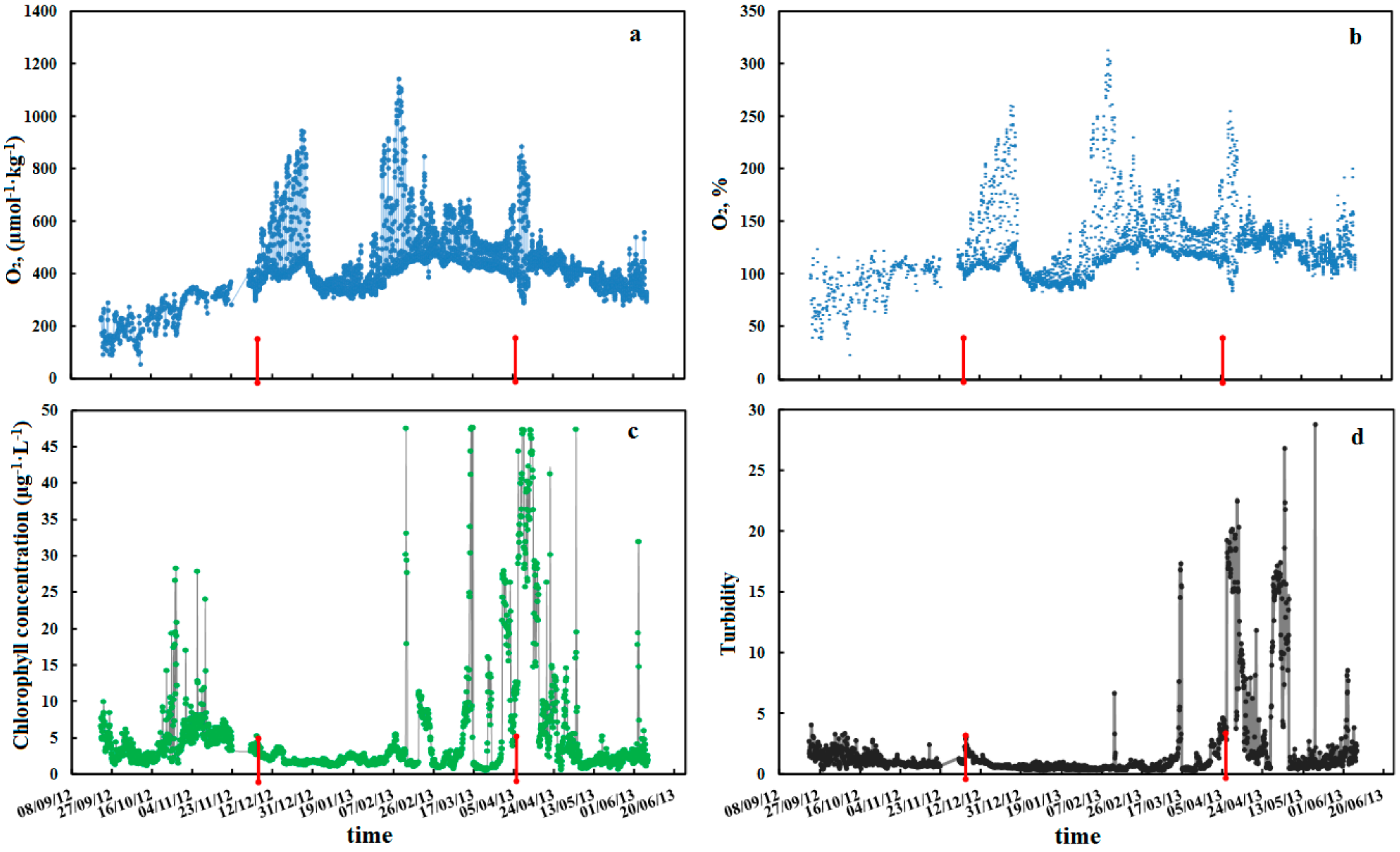

Fig. 3. Temporal variability of indicators (a – dissolved oxygen content, $\mu mol \cdot kg^{-1}$; b – oxygen saturation degree, %; c – chlorophyll concentration, $\mu g \cdot L^{-1}$; d – turbidity, Formazin Turbidity Unit, FTU) in the bottom water of the Voevoda Bay on 22.09.2012–07.06.2013 at WQM hydrological station (42°59.978′N, 131°47.659′E). Red lines mark the freeze-up period

It was found that diurnal anomalies in the oxygen content were related to changes in daylight (Fig. 4a). In our opinion, diurnal variations in the dissolved oxygen concentration (Fig. 4b) were associated with the photosynthetic activity of *Z. marina* and its physiological characteristics. The ranges of diurnal variations in the seawater saturation degree with oxygen were approximately 2–2.7 times higher than the values of the "baseline" (see Fig. 3b). Similar amplitudes of diurnal variations in the water saturation degree with oxygen in *Z. marina* meadows have been registered earlier (Long et al., 2019). The difference between our data and the results of the work, cited above, is in the value of the O_2 concentration of the "baselines". According to our measurements, this value is in the range of 100–130 % of saturation; in (Long et al., 2019), it is in the range of 50–75 % of saturation.

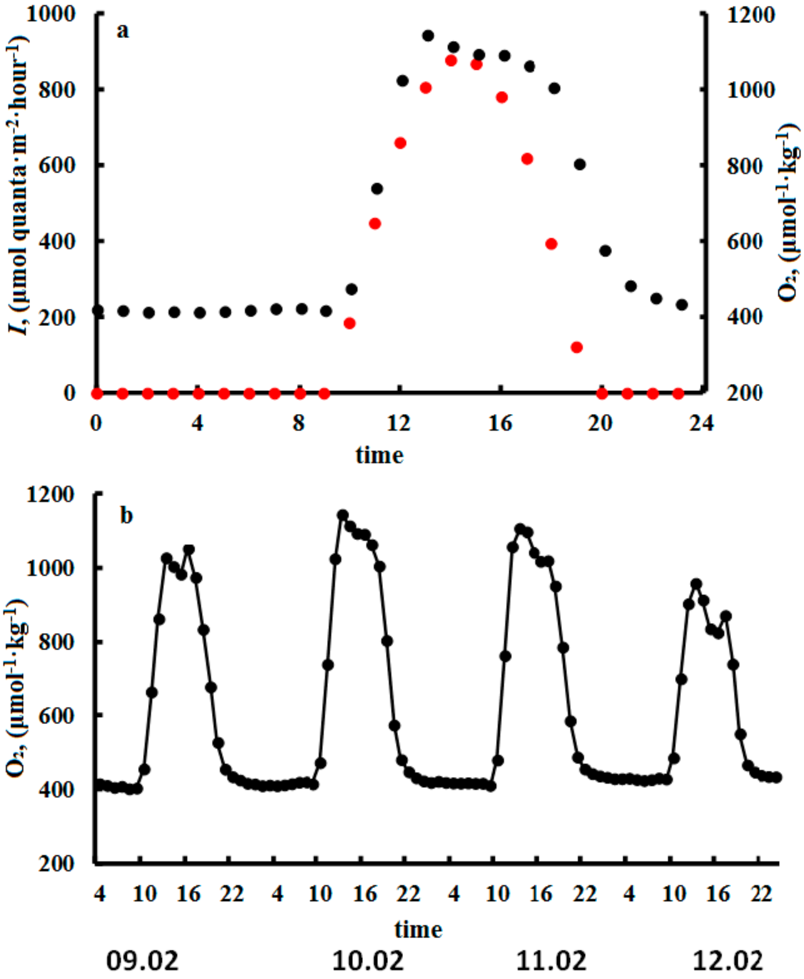

Fig. 4. Daily variability in the Voevoda Bay: a – light intensity, I, μmol quanta·m^{-2}·h^{-1} (red dots) and oxygen concentration, μmol·kg^{-1} (black dots) (10.02.2013); b – oxygen concentration, μmol·kg^{-1} (09.02.2013–12.02.2013)

DISCUSSION

An important peculiarity of *Z. marina* is its high production capacity: the average "net production" is 4.8 g C·m^{-2}·day^{-1} (McRoy, 1974). Eelgrass high productivity forms conditions for water supersaturation regarding atmospheric oxygen, up to the formation of air bubbles with an increased O_2 content on the surface of *Z. marina* leaves (Long et al., 2019). On the other hand, *Z. marina* high productivity results in the formation of silty sediments with significant concentrations of organic matter (Van Katwijk et al., 2010). Organic matter diagenesis in sediments in the areas of eelgrass growth leads to sulfate reduction, which can cause the meadows' die-off (Pedersen et al., 2004). The study of the Voevoda Bay sediment confirmed that sulfate reduction is an important manifestation of early organic matter diagenesis in this basin (Tishchenko et al., 2020a, b). In other words, the reduced sediments of the bay remove oxygen from the aquatic environment. Therefore, the long-term variability of the oxygen content in water is determined by the ratios of fluxes due to the oxygen production in the environment (photosynthesis), oxygen invasion/evasion at the water – atmosphere interface, and oxygen absorption by sediments.

At the beginning of monitoring (September 2012), the O_2 content was low: about 160 $\mu mol \cdot kg^{-1}$, or 60 % of saturation. High temperature and intensive decomposition of generative *Z. marina* leaves, intensively shedding in late July – early August (Lysenko, 1985 ; Paimeeva, 1984), were the main reasons for the low oxygen concentration and water saturation degree. Fluctuations in salinity and the O_2 content (see Figs 2, 3) were caused by wind mixing, which is a common phenomenon in late September – early October and leads to increased oxygen absorption by sediments. The minimum O_2 concentration (56 $\mu mol \cdot kg^{-1}$, or 24 %), corresponding to hypoxia, was recorded on 10 October. Then, an intensive increase in its content began; by early November, concentration increased up to 350 $\mu mol \cdot kg^{-1}$, or 110 % of saturation. A sharp decrease in temperature during this period (+18 to +6 °C) determined an increase in oxygen solubility and, accordingly, an increase in the atmospheric oxygen inflow into the aquatic environment. After generative leaves shedding, the production of *Z. marina* vegetative leaves increased (Lysenko, 1985), which also led to an increase in the O_2 concentration and even to water supersaturation with oxygen. The autumn peak in chlorophyll content (see Fig. 3c) did not affect the O_2 concentration. This fact indicates as follows: the oxygen flux, caused by *Z. marina* production/destruction at the water – atmosphere and water – bottom interface, was significantly higher than the oxygen production, caused by phytoplankton bloom. In December, immediately after the freeze-up period, high-amplitude positive fluctuations of oxygen were registered. The oxygen concentration (the "baseline") was slightly above 100 % of saturation and tended to increase up to 132 %, or 478 $\mu mol \cdot kg^{-1}$. During the freeze-up period, ice eliminated wind mixing and limited the effect of the atmosphere on the O_2 content in water; therefore, its production, resulting from sub-ice photosynthesis, and its removal by reduced sediments maintained the oxygen balance in water. Previously, we found that for ice with no snow coverage (60 cm thick), the flux of photosynthetically active radiation was sufficient to ensure sub-ice photosynthesis for all the Voevoda Bay depths (Barabanshchikov et al., 2015). It is obvious that in December 2012, the oxygen photosynthetic production dominated the respiratory processes and the O_2 removal by reduced sediments. According to the weather website (WindGURU, 2020), there was snow on 30 December (up to 3.3 mm in 3 hours), which led to a sharp decrease in the flux of photosynthetically active radiation into the water column. The oxygen concentration level began to decrease and reached values of 312–360 $\mu mol \cdot kg^{-1}$, or about 90 % of saturation (see Fig. 3a, b). At the end of January, the snow on the ice surface began to disappear, the "baseline" again reached 100 % and even slightly exceeded it. The oxygen content in sub-ice water in the period February to March (before ice cover break-up) was at the level of 103–133 %; at the same time, positive anomalies of O_2 concentration were observed in the daytime (Fig. 4). According to the weather website (WindGURU, 2020), there was rain on 6 April (up to 0.9 mm in 3 hours), and strong north wind (13 $m \cdot s^{-1}$) was blowing. The wind and positive air temperatures led to both ice cover break-up and fast ice break-up.

The ice cover break-up and melting resulted in a sharp change in the illumination of water, causing a peak of phytoplankton bloom and an anomalous O_2 concentration. During this period, negative oxygen anomalies were also observed, which seemed to be associated with the beginning of the wind movement of water in the Voevoda Bay and an increase in the rate of the O_2 removal by reduced sediments. The subsequent spring decrease in oxygen concentration was mainly due to a seasonal increase in temperature; however, water remained supersaturated (about 120 %) regarding atmospheric oxygen until the end of monitoring.

To estimate the maximum rate of O_2 production, the maximum diurnal oxygen anomaly on 10.02.2013 was chosen (see Fig. 4b). For the interval 9:00–13:00, an empirical fourth-order relationship of oxygen concentration on time was obtained. A time derivative of this relationship gave the rate of an increase in the O_2 content in the aquatic environment – 307 $\text{mmol}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$. By calculation method for average depth of the Melkovodnaya Bay (2 m), the production rate of 614 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ was obtained. Obviously, this rate value depends on the density of *Z. marina* meadows (in our case, 3 kg of wet weight per 1 m^2) (Barabanshchikov et al., 2018). As a result, the maximum oxygen production rate per 1 g of *Z. marina* wet weight was obtained – 6.5 mg $O_2\cdot\text{h}^{-1}\cdot\text{g}^{-1}$; it was approximately three times higher compared to that from (Berger, 2011). The resulting rate value corresponded to 11:00 local time.

A similar calculation for the descending branch of the oxygen anomaly gave the maximum rate of oxygen "removal" from the aquatic environment, relative to 1 g of *Z. marina* wet weight: −5.0 mg $O_2\cdot\text{h}^{-1}\cdot\text{g}^{-1}$; it corresponded to 19:00 local time. This high rate of the O_2 "removal" from the environment is surprising, since *Z. marina* and other seagrass use oxygen for respiration in the range of 10–30 % of the maximum production value (Borum et al., 2007). In our case, the "removal" was 76 % of the production. We use quotation marks to indicate the rate, at which the oxygen concentration decreases, because we believe this value to be apparent and be the result of complex processes, caused by *Z. marina* anatomical and physiological peculiarities, as well as short-term changes in the external environment (tides).

Zostera marina is a higher vascular perennial plant with a rhizome, on which vegetative and generative shoots develop (Paimeeva, 1984). One of eelgrass anatomical features is the air lacunae in its leaves, rhizome, and roots. *Z. marina* physiological peculiarities make it possible to accumulate oxygen in the air lacunae in the leaves due to photosynthesis, to transport oxygen to the roots, and to provide an aerobic microenvironment in the immediate vicinity of the roots in anaerobic sediments (Borum et al., 2007). The oxygen release into the aquatic environment by vascular plants can be provided by two mechanisms: diffusion and bubble formation (Colmer, 2003). We assume that at the initial stage, with the onset of daytime, photosynthesis in *Z. marina* leaf cells increases the partial pressure of oxygen in the air lacunae. This process causes oxygen diffusion into the seawater. By 11:00, the partial pressure of oxygen in seawater reaches 2-fold water supersaturation regarding the basic oxygen supersaturation, with its value being higher in the air lacunae. Direct measurements of the partial pressure of oxygen in the air lacunae indicate a value of more than 200 % (Sand-Jensen et al., 1985). We assume that in this state, *Z. marina* leaves release oxygen-enriched air bubbles, that float to the inner ice surface and go into the ice pores and further into the atmosphere. A similar possibility of gas exchange between the atmosphere and sea ice has been demonstrated for carbon dioxide (Semiletov et al., 2004). By 13:00, the process of gas transfer becomes dominant; therefore, further photosynthesis does not lead to an increase in oxygen concentration in seawater. It should be noted that irregular semidiurnal fluctuations of the water level with an amplitude of 30–50 cm are characteristic of Peter the Great Bay, including the Voevoda Bay (Supranovich & Yakunin, 1976). The values of hydrostatic pressure, registered by the WQM station from 9 February to 12 February 2013, indicate that the maximum amplitude of the anomalies for the studied bay is 46 mbar (Fig. 5), which is consistent with the previously presented data (Supranovich & Yakunin, 1976).

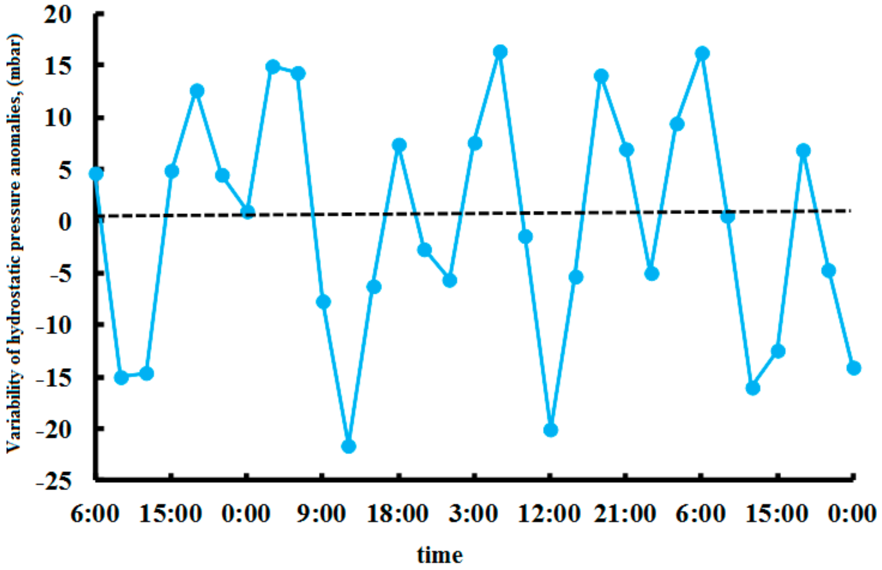

Fig. 5. Variability of hydrostatic pressure anomalies, mbar, in the Voevoda Bay for 09.02.2013–12.02.2013

Tides can be described as short-term variability in the environment, capable of influencing the O_2 concentration in seawater, since hydrostatic pressure anomalies affect the partial pressure of oxygen in *Z. marina* air lacunae. From 06:00 to 12:00, the Voevoda Bay experiences a low tide, during which negative hydrostatic pressure anomalies arise, causing the oxygen transfer from *Z. marina* into the seawater *via* the bubble mechanism (Long et al., 2019). From 06:00 to 9:00 on 10.02.2013, the positive anomaly (14.3 mbar) changed to a negative anomaly (−7.7 mbar) due to the low tide (see Fig. 5). During this time interval, the O_2 concentration in the aquatic environment practically did not change. With the onset of daylight (about 09:00), a sharp increase in the oxygen content began. The maximum oxygen supersaturation (314 %) was recorded on 10.02.2013 at 13:00 (see Fig. 3b), and the maximum rate of an increase in the O_2 concentration with 2-fold supersaturation of water regarding air oxygen was registered at 11:00. We assume that after 11:00, due to water supersaturation with oxygen and a negative hydrostatic pressure anomaly (−21.6 mbar at 12:00), oxygen was released from *Z. marina* into the marine environment *via* the bubble mechanism. From 12:00 to 18:00, an increase in hydrostatic pressure was recorded, which pushed air bubbles with an increased oxygen content from seawater into the ice pores and further into the atmosphere. After noon, photosynthesis weakens, the intensity of photosynthetically active radiation decreased (see Fig. 4a); these factors, in combination with increasing hydrostatic pressure, contribute to the oxygen flow from seawater to *Z. marina* aerenchyma and then along the air lacunae to the roots and sediments (Borum et al., 2007). The internal oxygen flow through the air lacunae in the eelgrass can be both diffusional and supramolecular. For example, the internal air flow rate for a reed (also a vascular plant) reaches 50 $mL \cdot min^{-1}$ (Colmer, 2003). As established, oxygen, supplied by *Z. marina* to the reduced sediments of the bay, is spent on the oxidation of hydrogen sulfide and sulfides (Borum et al., 2007); accordingly, the observed rate of oxygen removal cannot be used to assess the rate of its consumption for eelgrass respiration. It should also be noted that an almost unchanged level of oxygen concentration is observed at night (see Fig. 4b). The rate of oxygen consumption for *Z. marina* respiration is 20 % of the maximum production (Borum et al., 2007). For the existing population density of the eelgrass meadows in the Voevoda Bay, the rate of oxygen consumption was of -61 mmol·m^{-3}·h^{-1}. Such a rate had to be recorded by the oxygen sensor, and then we could observe a decrease in its content in water at night, but it was not the case. Therefore, it was assumed that the amount of oxygen in the air lacunae is quite high, and they play the role of a buffer system in maintaining a stable oxygen concentration at night.

Conclusion. Two types of oxygen concentration variability in the Voevoda Bay environment have been established: 1) long-term variability, caused by seasonal variations in the environment; 2) daily variability during the freeze-up period, determined by the intensity of photosynthetically active radiation penetration into sub-ice water. In the autumn period, low O_2 concentrations, up to hypoxic level, were observed; in the winter and spring seasons, the oxygen content was recorded at 100–130 % of saturation. High daily variability was registered during the freeze-up period, with no snow coverage. In February, the amplitude of daily fluctuations in the O_2 concentration reached 730 µmol·kg^{-1}, with 3-fold supersaturation regarding atmospheric oxygen. It was established that the maximum rate of oxygen production, relative to 1 g of *Z. marina* wet weight, is 6.5 mg O_2·h^{-1}·g^{-1}. The daily dynamics of oxygen in seawater is affected by eelgrass physiological peculiarities: air lacunae in its shoots can play the role of a buffer system in maintaining a stable oxygen concentration at night. Semidiurnal tides in the water area of the bay, affecting the air lacunae, increase or decrease the oxygen flow from *Z. marina* into the seawater in the corresponding period of low tide or high tide.

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ОСОБЕННОСТИ ВРЕМЕННОЙ ИЗМЕНЧИВОСТИ СОДЕРЖАНИЯ КИСЛОРОДА В ЗАРОСЛЯХ *ZOSTERA MARINA* LINNAEUS, 1753 В БУХТЕ ВОЕВОДА (АМУРСКИЙ ЗАЛИВ, ЯПОНСКОЕ МОРЕ)

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В настоящее время мелководные бассейны с лугами *Zostera marina* L. рассматривают в качестве поглотителей атмосферного углекислого газа, способных сдерживать увеличение его концентрации. Благодаря своей высокой продуктивности взморник выделяет в среду большое количество кислорода. Для установления особенностей проявления продукционной активности мелководных бассейнов, покрытых лугами *Z. marina*, на примере бухты Воевода (Амурский залив, Японское море) проведён мониторинг гидрологических и продукционных параметров с различными интервалами измерений. Наблюдения продолжались 8,5 мес. (22.09.2012–07.06.2013). В зарослях *Z. marina* на глубине 4 м измеряли температуру, солёность, флуоресценцию хлорофилла и мутность с помощью гидрологической станции Water Quality Monitor с интервалом 3 часа. Малоинерционным оптическим кислородным датчиком ARO-USB определяли концентрацию растворённого кислорода с интервалом 1 час. Установлено два типа изменчивости содержания кислорода в среде: 1) долгопериодная изменчивость, обусловленная сезонными изменениями среды; 2) суточная в период ледостава, определяемая интенсивностью проникновения фотосинтетически активной радиации в подлёдную воду. В осенний сезон отмечены низкие концентрации кислорода, достигающие уровня гипоксии. Для зимнего и весеннего периодов содержание кислорода находилось, как правило, на уровне 100–130 % от насыщения. Высокую суточную изменчивость наблюдали в период ледостава, в отсутствие снега. В феврале амплитуда суточных колебаний концентрации кислорода достигала 730 мкмоль·кг$^{-1}$, с трёхкратным пересыщением по отношению к атмосферному O_2. Установлено, что максимальная скорость продукции кислорода, отнесённая к 1 г сырой массы *Z. marina*, составляет 6,5 мг O_2·час$^{-1}$·г$^{-1}$. Суточная динамика кислорода в морской воде проанализирована в связи с физиологическими особенностями *Z. marina* (воздухоносные полости в побегах играют важную роль в динамике кислорода в среде), а также в связи с короткопериодными приливами.

Ключевые слова: *Zostera marina* L., макрофиты, растворённый кислород, бухта Воевода, Амурский залив, Японское море